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Considering cognitive biases in design: an integrated approach

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Abstract

Design is a dynamic, decision-driven process, often guided by intuition and experience. It can be susceptible to cognitive biases, systematic deviations in information processing and decision making, which have been recognized as influential factors affecting expert judgment in multiple domains. Although some studies in the design field have investigated and proposed methods to address specific biases, such as the confirmation bias, there is currently no comprehensive approach in the literature to make designers aware of the various biases that may manifest during the design process. The main contribution of this article is to provide designers with a broad overview of the biases that may be involved within the three principal areas of design cognition: problem formulation, concept generation and concept evaluation. It also proposes a novel and workable methodology to facilitate designers' recognition and mitigation of biases through metacognition, while favoring the implementation of more specific correction strategies.

Keywords: Cognitive biases; decision-making; bias classification; design cognition; design activities, metacognition; debiasing methodology.

1. Introduction

Cognitive biases refer to systematic deviations that arise during information processing and decision making, which often lead to suboptimal judgments [1], [2]. These biases can be triggered by cognitive heuristics, which are unconscious mental shortcuts or rules of thumb employed to enhance the efficiency of information processing [3]. Because cognitive biases are inherent in human nature, individuals are often unaware of their influence and occurrence. Consequently, even well-intentioned professionals and experts can be vulnerable to making biased decisions [4], [5]. In fact, research has shown that many biases are uncorrelated with cognitive ability or intelligence [6].

Cognitive biases have been identified and studied in various fields such as finance and economics [7], software engineering [8], and medical decision making [9]. Although some studies have discussed specific biases in product

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and engineering design, such as confirmation bias [10]; literature in the design field does not comprehensively address the various sources of biases that can exist in the design process, nor does it provide a clear understanding of how designers can be influenced by biases throughout it. This article aims to provide an overview of cognitive biases in design, recognize potential sources of bias, and suggest strategies for mitigating or eliminating them.

The article is structured as follows: Section 2 introduces the notion of cognitive biases and examines its application in the context of design, highlighting gaps in the current literature, and presenting selected taxonomies of cognitive biases. In Section 3, a model of design activities that connects key areas of design cognition and design reasoning activities is proposed, allowing exploration of the cognitive biases that may affect designers during these activities. Section 4 provides a concise self-assessment methodology aiming to mitigate the influence of cognitive biases on designers and offers an illustrative example to demonstrate its application. Finally, the contributions of this study are discussed, and avenues for future research are proposed.

2. Background

2.1. Cognitive heuristics and biases

A widely accepted model for explaining how individuals make decisions is the dual-process theory, also known as the dual-system process [7]. According to this psychological framework, human cognition and decision-making are influenced by two distinct cognitive processes or systems that operate in parallel. *System 1* is fast, automatic, effortless, associative, and difficult to control or modify. *System 2*, on the other hand, is slower, serial, effortful, and deliberately controlled. The first system is typically used unconsciously and relies on experience for decision-making. Moreover, it is independent of individuals' cognitive ability. In contrast, the second system is based on rules, seeks to make consequential decisions, and may be related to people's cognitive capacity [11].

The low cognitive load represented by the use of *System 1* makes it efficient, and very useful in everyday situations where it would not be practical to deliberately reason through every choice [12]. It is also highly valuable in dynamic, fast-paced environments such as intelligent production planning systems, where fast response time is crucial [13]. However, this reliance on the fast system can also lead to systematic errors in judgment, also known as cognitive biases, affecting decision making and distorting individuals' judgments, resulting in suboptimal choices.

2.2. Cognitive biases in design

Different studies have suggested the presence of cognitive biases within the design domain. For instance, Viswanathan and Linsey [14] explored the impact of the sunk cost effect on design fixation through a controlled study. The sunk cost effect refers to the tendency to persist with a project or decision, even when it no longer provides significant benefits, because of prior resource investments (time, money, or effort). The study confirmed the significant role of the sunk cost effect in fixation and suggested using materials that minimize time and cost when creating physical models. Another bias known as confirmation bias, which refers to the inclination to seek, interpret, and favor information that aligns with pre-existing beliefs or hypotheses, while dismissing or discarding contradictory evidence, was identified in design by Hallihan et al. [10]. To mitigate this bias, the researchers proposed the use of a simplified matrix based on the Analysis of Competing Hypotheses method [15], to evaluate and compare ideas.

In another paper [11], Kannengiesser and Gero examine the connection between dual-system theory and design thinking, using the function-behavior-structure ontology as a framework. The primary objective of their research is to establish a foundation for enhancing design tools by identifying the locations of the two modes of design thinking. This article makes a significant contribution by providing a more comprehensive perspective that encompasses different instances of design, providing valuable insights into situations where designers may be particularly susceptible to biases arising from the implementation of *System 1* thinking. However, the number of biases stemming from the use of *System* 1 thinking can be quite extensive. Therefore, identifying and localizing the use of this system is not sufficient to establish the specific biases that designers may face.

In summary, recent studies have highlighted the importance of developing methodologies in the design field that help overcome biased judgments resulting from relying on *System 1* thinking, by encouraging the use of *System 2* to verify and evaluate intuitive work. This emphasis holds significant relevance because, even within the domain of smart manufacturing, where data analytics and intelligent planning algorithms provide substantial support, human decision-making remains a fundamental aspect in shaping production systems [13]. Although some studies have identified specific biases during the design process and proposed corresponding solutions, we are unaware of the existence of an integrated methodology that would enable designers to identify these biases easily and practically at each stage of their work, allowing them to re-evaluate it while exploring more specific debiasing techniques. Identifying biases that could affect designers' reasoning, requires a taxonomy that shows the connection between design activities and specific biases. Some classifications that may be relevant to this more practical approach are explained below.

2.3. Task-based taxonomy of biases

Different classifications, especially in the field of psychology, seek to provide a better understanding and organization of cognitive biases. Some taxonomies are based on the dual-system theory, according to the heuristics deployed by individuals [1]. However, there is still no agreement on the specific causes of cognitive biases or the best way to classify them [16]. Consequently, classifications aiming to understand the reasons behind cognitive biases may appear ambiguous, as various authors adopt distinct terminologies and attribute varying origins to the same biases.

Even if understanding the nature of biases is an important issue, a more practical approach is necessary to facilitate the assignment of biases according to the different activities performed by designers. In pursuit of a more pragmatic approach, Dimara et al. [17] proposed a task-based taxonomy comprising 154 cognitive biases, organized into six primary categories. The taxonomy aims to categorize biases based on the specific tasks in which they were observed and measured in previous experimental research. The categories include *estimation*, *decision*, *hypothesis evaluation*, *casual attribution*, *recall*, and *opinion reporting*. All these tasks are implicit in the design process, in which designers estimates the performance of design solutions, decide between alternative methods, strategies and concepts, make use of their memory to recall past experiences or to take requirements into account during the proposal of ideas, and evaluate design hypotheses. The categories of *opinion reporting* and *causal attribution* may be the least related to this process, as designers rarely must express their opinions on social, or moral issues, or question the work of others.

2.4. Taxonomy of cognitive bias sources

To organize the information on designers' behavior and infer which cognitive biases may arise during the different cognitive activities they perform, we will rely on a taxonomy of eight cognitive biases proposed by Dror [5]. These sources represent the factors that can generate a fertile environment for the appearance of cognitive biases, although originally this taxonomy was intended to address the expert decision-making domain, it can be easily adaptable to the area of product or system design. Figure 1 presents examples of sources that could be found in the design field.

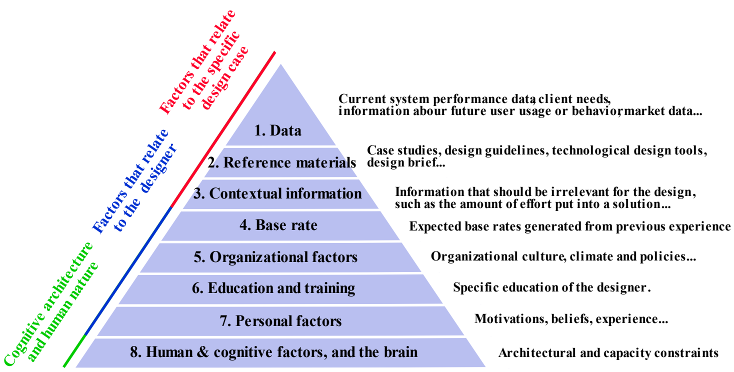

Fig. 1. Sources of cognitive bias in design, adapted from [5].

As we can notice, the sources range from those relating to a specific design case, to those relating to the decision maker, in the case of this study, the designer. This classification will be used to analyze the sources specific to design and identify how they might generate a favorable environment for biased judgments.

3. Proposal of a generic model of design activity-related biases.

The proposed generic model of design activities for this study (see Table 1) encompasses six reasoning activities that can be iteratively applied to different design problems to define and achieve specific objectives [18], [19]. Given that cognitive biases predominantly arise from a reliance on *System 1* thinking [12], activities that are fully deterministic and rely exclusively on *System 2* will be excluded from the study. Reasoning activities are linked to the three main areas of design cognition [20], [21]. Firstly, *problem formulation* involves a thorough understanding of the design problem, identifying goals, and defining constraints and requirements. Secondly, *concept generation* involves generating and synthesizing ideas into more refined or complete solutions. Lastly, *concept evaluation*, involves evaluating concepts against the constraints, criteria, and design requirements defined during problem analysis.

Table 1. Generic model of design activities.

Design reasoning activity	Short definition	Link with design cognition
Specify	Document, and describe essential elements and requirements, refining design proposal for precise guidance in subsequent stages.	Problem formulation
Imagine and create	Generate innovative design solutions, leveraging specified requirements, through creative problem-solving and imagination.	Concept generation
Dimensioning	Determine optimal physical dimensions based on design assumptions, considering technical, economic, and regulatory factors.	Concept evaluation
Represent	Formalize solution using visual, textual, or digital means.	Deterministic
Evaluate and optimize	Iteratively improve design, considering various criteria, by comparing requirements to final solution results.	Concept evaluation
Validate	Approve optimized model based on time, cost, performance, and other criteria to confirm customer specifications.	Deterministic

To infer which cognitive biases affect different cognitive activities in design, we rely on the behavior exhibited by designers during these activities, described mainly by Cross in his review of design protocols [20]. We identified the main sources of cognitive biases that could create a fertile environment for errors in designers' judgment, and clues suggesting the potential development of specific biases. These initial clues were supplemented by the brief discussion of cognitive biases that might affect design, proposed by Hallihan et al. [10]. Finally, to explain in which specific types of tasks these biases could be generated, we rely on the task-based taxonomy of cognitive biases [17].

3.1. Problem formulation: Insights about designers and sources of bias identification

To correctly formulate the design problem and its constraints, the designer must rely on data and information to understand the behavior and performance of the current and desired system, the user's interaction with the system or product to be designed, the time and constraints available to develop the design, and so on. The way this data is presented to the decision maker (Source 1 of bias), combined with the way the human brain processes the information (Source 8), can be important sources of cognitive biases. Remus and Kottemann [22] summarized the human input errors that can bias data interpretation, they explained for instance that information and data obtained through human interaction tend to have a stronger influence on decision-makers, as well as the data presented in graphical form. Furthermore, they suggest that individuals tend to filter information based on their personal experiences (Source 7).

Lawson [23], in his study on problem-solving strategies, compared the behavior of scientists and architectural designers, and identified that the former adopted a solution-focusing strategy more centered on the structure and formulation of the problem, while the latter operated a solution-focused strategy. However, when repeating the same experiment with first-year students of science and architecture, he found no such differences, so it seems that these behaviors are influenced by education and experience (Source 6,7, 8). While this solution-oriented problem definition approach cannot be deemed inherently wrong, as the co-evolution of problem-solution allows designers to explore the space of possible solutions and redefine the problem [24], it might suggest that spending less time on problem definition could make designers more susceptible to biases related to information presentation.

3.1.1. Identifying bias-related tasks in problem formulation

During the specification activity, designers must organize and prioritize client and system requirements. This involves determining key criteria for proposing solutions in subsequent design stages. To assess the importance of different criteria, designers could rely on estimates of how frequently these criteria have been important in past projects. This is based on the *availability heuristic*, which estimates the frequency of an event based on how easily instances or associations come to mind. However, recall can be influenced by different factors beyond frequency. For instance, designers may remember constraints, criteria, or solutions that required significant effort to comprehend, a phenomenon known as the *processing difficulty effect*. Likewise, designers might have an easier time recalling criteria presented in visual formats, thanks to the *picture superiority effect*. Additionally, they may exhibit faster recall of the first and last elements of the information they read, influenced by the *serial-positioning effect*.

In addition, during the specification, the task of deciding which priorities and main requirements to establish takes place. This task may be influenced by the previous biased estimates and by some new biases. For example, the *framing effect* might affect the designer's choice between two options depending on how the positive or negative results of each option are presented, the *mere-exposure effect* might lead the designer to privilege familiar information, and the *attraction effect* might cause the designer to choose to work with certain criteria that appear to be important in contrast to others but might not necessarily be useful. A matrix that summarizes the identification of biases in problem formulation is presented in Figure 2.

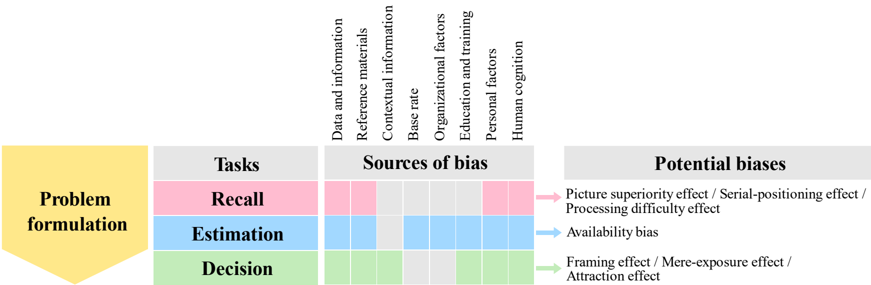

Fig. 2. Bias recognition matrix for problem formulation.

3.2. Concept generation: Insights about designers and sources of bias identification

Design problems often cannot be fully defined, which is why the solution-focused behavior of designers can be advantageous and realistic. However, overreliance on this behavior can lead to a well-known effect in design, the fixation effect [20], which refers to the attachment to a limited set of ideas during the design process, causing some designers to prefer reusing features from existing designs rather than exploring and creating new ones [25]. This could be related to the use of reference materials (Source 2), such as industry standards, case studies, design catalogs, or even the designers' own experience (Source 7), used as inspiration to propose solution ideas.

Purcell and Gero [26], [27], conducted a series of experiments in which senior students of industrial design and mechanical engineering were asked to propose concepts and solutions after being shown examples of previous designs. The results showed that engineers' designs were strongly influenced by the examples, whereas industrial designers tended to produce a greater variety of uninfluenced designs, suggesting that engineers are much more prone to fixation. This could possibly be because, during their education (Source 6), industrial designers are more encouraged to generate diverse design solutions than engineers. Several studies have observed that designers also show a strong attachment to their initial design ideas [28], [29]. Even when major problems are detected, they are reluctant to discard these proposed solutions, preferring instead to invest effort in refining them until they have something workable.

3.2.1. Identifying bias-related tasks in concept generation

We suggest that although designers may also be influenced this time by biases observed during recall tasks (*picture superiority effect*, *processing difficulty effect* or *serial-position effect*), it is more likely that the effects of memory will be reflected in the estimation of the feasibility and utility of the envisioned solutions. This is because designers are not directly engaged in recall tasks, but rather in tasks involving the estimation of the performance of the imagined concepts or ideas, and it is these estimations that may be biased by recall effects. Once again, designers may be affected by *availability bias*, but they may also have to deal with *anchoring bias*. For example, if a designer encounters a standard, reference or idea initially proposed by someone else, it is possible that this information becomes an anchor or dominant starting point and establishes a frame of reference for his or her thinking, limiting their ability to explore alternatives beyond that established starting point.

Finally, as during the problem formulation phase, designers will also have to make decisions, such as determining which idea or ideas they want to develop and evaluate, thus they could be equally affected by decision biases (the *mere-exposure effect*, the *attraction effect,* or the *framing effect*). For example, if designers were presented with a negatively framed or constraint-focused problem or challenge, they would be more likely to choose conservative and conventional solutions. Conversely, if the problem were posed to them in a positive or opportunity-focused way, they would be more likely to choose innovative solutions. The bias recognition matrix for this cognitive activity is presented in Figure 3.

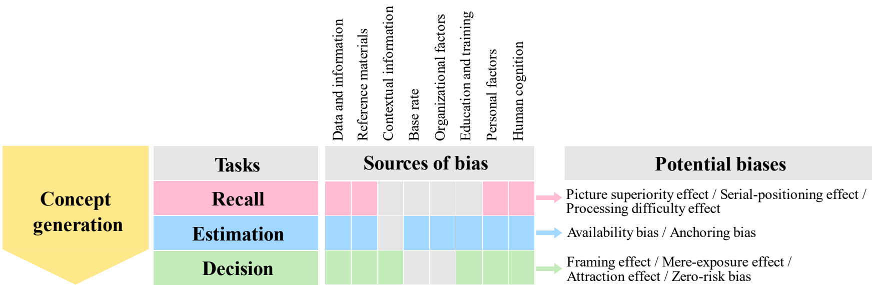

Fig. 3. Bias recognition matrix for concept generation.

3.3. Concept evaluation: Insights about designers and sources of bias identification

In the proposed activity model, *concept evaluation* encompasses *dimensioning* and *evaluation activities*, as they help to verify the relevance of solutions and involve subjective or intuitive components. During *dimensioning*, deterministic methods and engineering tools such as strength analysis, deformation calculations, and prototype testing are employed. Nevertheless, there are also stages within this process wherein designers may need to rely on subjective assumptions or hypotheses related to load conditions, material properties, or other uncertain variables, such as all possible uses of the system or product. During *evaluation*, different solutions are compared among themselves or against requirements to determine the most fitting solution and identify opportunities for optimization or improvement of that solution. During these comparisons, judgment can also be based on subjective aspects, such as aesthetics [21].

While performing these activities, designers may be susceptible to biases associated with the reference materials they rely on for analysis and evaluation, such as industry standards, or chosen evaluation methods (Source 2). While these resources can provide valuable guidance for design, they may not always be applicable or suitable for a specific design. Given that design is a multidisciplinary field, it is natural for designers to have knowledge or experience gaps (Sources 6, 7) in certain areas such as ergonomics, or environmental factors. However, companies and organizations, driven by their policies, (Source 5), require designers to incorporate specific standards from these domains into their designs. Therefore, the implementation of these norms can pose challenges for designers [30], as they may find themselves making uninformed or suboptimal decisions. Furthermore, it has been observed that the representation of solutions or the construction of physical models can impact the evaluation and optimization of solutions. This is because, when significant resources have been invested in a solution, designers are less likely to discard it [14].

3.3.1. Identifying bias-related tasks in concept evaluation

In addition to engaging in memory, estimation, and decision-making tasks and, therefore, being subject to all the biases mentioned above; during *concept evaluation* designers will also have to evaluate their assumptions and hypotheses. For example, assumptions made during dimensioning or during alternative evaluation. Consequently, they may be susceptible to *confirmation bias*. This bias leads them to favor information, data, and evidence that support their hypotheses while conducting a cursory search for information that contradicts them. As a result, they may experience potential false confirmations of their hypotheses and accept *illusory correlations* that are not grounded.

Lastly, the *hindsight bias* can affect the ongoing evaluation of concepts and design solutions. It involves perceiving an event as predictable after knowing its outcome, even if it was not actually predictable. This bias hinders learning from past events, restricting designers' capacity to improve and adapt their approaches or solutions. Figure 4 shows the biases that we could theoretically encounter during concept evaluation.

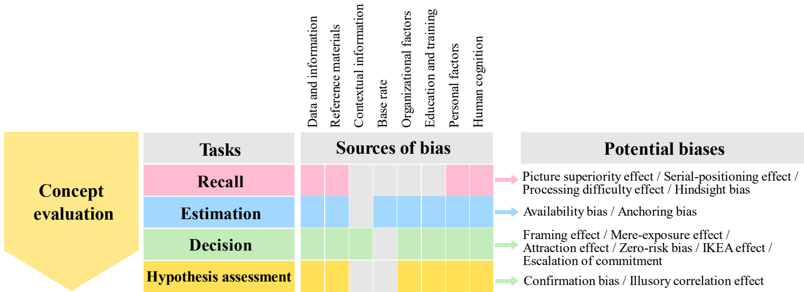

Fig. 4. Bias recognition matrix for concept evaluation.

4. A methodology for considering biases during the design process.

By adopting a reflective approach, proven effective with engineering students in motivating their learning and consideration of cognitive biases in their work [31]; and encouraging designers to slow down and employ *System 2* to monitor the performance of *System 1*, as advocated by Kannengiesser and Gero [11], we propose a seven-step methodology to mitigate cognitive biases in design (see Table 2). This methodology aims to enhance designers' metacognition, which refers to their knowledge and awareness of their thinking process, and establish connections, through self-assessment, between the design process and methods focused on combating specific biases.

Table 2. Proposed debiasing methodology.

Proposed debiasing methodology steps	Who?	Tools
1. Specify the design tasks.	The designer	Generic model of design activities
2. Build the list of potential cognitive biases involved in the project according to the cognitive activities considered.		Bias recognition matrix
3. Construct the questionnaire to be submitted to the designer.		Cognitive Bias/Question Table
4. Respond to the questionnaire.	The designer	
5. Identify the cognitive biases that the designer encountered during the project.		Questionnaire response rules
6. Propose recommendations to the designer to reduce or eliminate the effects of identified biases on their activity.		Not addressed in this approach
7. Conduct a review and self-evaluation of the work performed.	The designer	

4.1. Identifying cognitive biases in practical design applications.

For a better understanding of the debiasing methodology, we present an illustrative example of its practical application. We will examine a scenario in which a designer is tasked with defining the trajectories and postures of an operator during the development of a new workstation. The current section describes the steps the designer needs to take to effectively implement the proposed debiasing methodology.

4.1.1. Step 1: Specify the design tasks by relating them to the proposed six reasoning activities, if applicable.

In this first stage, the designer must delimit the design tasks, based on the framework provided by the generic model of design activities (see Table 1). In the context of our proposal, we have identified and specified seven distinct design tasks:

1) Precisely identify the tasks that the operator will need to perform / **Specify (Problem formulation)**.
2) Create the necessary geometric context for the study / **Specify (Problem formulation)**.
3) Identify the ergonomic anthropometric characteristics of the operator / **Dimensioning (Concept evaluation)**.
4) Propose solutions for the operator's movements and postures to meet the tasks they need to perform in the work environment / **Imagine and create (Concept generation)**.
5) Model the operator's trajectories and postures / **Represent (Deterministic)**.
6) Conduct an ergonomic analysis of the proposed solutions / Evaluate and optimize **(Concept evaluation)**.
7) Choose a final solution / **Validate (Deterministic)**.

4.1.2. Step 2: Build the list of potential cognitive biases involved in the project according to the cognitive activities considered.

Considering that the designer wants to evaluate their work after completing only the first two tasks corresponding to **problem formulation** activities, the necessary matrix for identifying potential biases is presented in Figure 5.

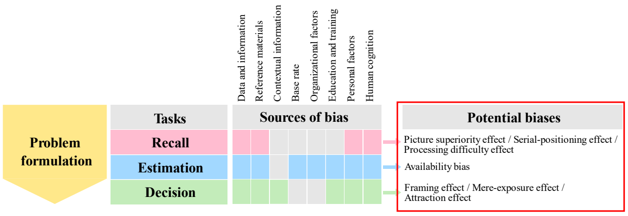

Fig. 5. Application of the bias recognition matrix for problem formulation.

4.1.3. Step 3: Construct the questionnaire to be submitted to the designer, Step 4: Respond to the questionnaire & Step 5: Identify the cognitive biases that the designer encountered during the project.

In this stage, the designer is required to construct a questionnaire based on the questions outlined in Table 3.

Table 3. Cognitive Biases/Questions Table.

Bias to be identified	Corresponding question
Recall biases	Are the choices/solutions you've made related to recent memories?
Availability bias	Have you privileged your memories/experiences?
Anchoring bias	Have you favored choices/solutions based on initial recommendations, data, or references without thoroughly evaluating them against other options?
Framing effect	Have you favored choices/solutions where both the advantages and disadvantages have not been clearly presented?
Mere-exposure effect	Are the choices/solutions familiar to you, either through personal exposure or by being aware that others have also worked with them?
Attraction effect	Have you favored options/solutions that appear less disadvantageous in contrast (even if not highly advantageous)?

Confirmation bias	Have you prioritized information that confirms your existing beliefs or hypotheses, potentially overlooking contradictory evidence in your design decisions?
Illusory correlation effect	Have you attributed cause-effect relationships between your design choices/solutions and expected outcomes without substantial evidence to support them? (e.g., assuming that increasing machine speed will result in overall cost reduction)
Zero-risk bias	Have you favored choices/solutions that completely eliminate a specific risk?
IKEA effect	Have you favored choices/solutions that required significant work or effort from you?
Escalation of commitment / Sunk cost	Have you persisted with choices/solutions that required a significant financial or material investment, despite the presence of better alternatives?
Hindsight bias	Do you think that the failures or shortcomings of the decisions/solutions analyzed should have been easily foreseeable from the beginning?

To do so, the designer must identify the questions associated with the potential biases identified in the previous step and respond to them using one of the three response options: “Yes”, “No”, or “Not sure” (see Table 4).

Table 4. Application of the Cognitive Biases/Questions Table. Responding "Yes" suggests susceptibility to the bias, "No" implies a lower likelihood of susceptibility, and "Not sure" is treated as "Yes" for enhanced method.

Bias to be identified	**Question**	**YES**	**NO**	**NOT SURE**
Recall biases	Are the choices/solutions you've made related to recent memories?		X	
Availability bias	Have you privileged your memories/experiences?		X	
Framing effect	Have you favored choices/solutions where both the advantages and disadvantages have not been clearly presented?			X
Mere-exposure effect	Are the choices/solutions familiar to you, either through personal exposure or by being aware that others have also worked with them?	X		
Attraction effect	Have you favored options/solutions that appear less disadvantageous in contrast (even if not highly advantageous)?		X	

In this case, the designer should consider that they might have been influenced by the Mere-exposure effect and the Framing effect. Even if they responded "Not sure" to the Framing effect question, it is advisable to assume a potential susceptibility to it for greater confidence in the methodology.

4.1.4. Step 6: Propose recommendations to the designer to reduce or eliminate the effects of identified biases on their activity & Step 7: Conduct a review and self-evaluation of the work performed.

These steps correspond to an expansion of the designer's understanding of the identified biases, a self-evaluation of their design work, and the application of more specific methods to mitigate and correct the effects of the identified biases. However, these strategies are not directly proposed or discussed in this approach.

5. Conclusion and perspectives

During the design process, designers may encounter various biases that can distort their perception, memory, and reasoning, leading to biased conclusions and weak solution proposals. These biases can manifest across all cognitive activities in design and may stem from design-specific sources. This article raises awareness among designers about the existence of these phenomena and their potential consequences in *problem formulation*, *concept generation*, and *concept evaluation*. Besides, a practical bias mitigation methodology has been proposed, encouraging designers to engage in reflection and self-evaluation throughout the design process. This methodology can be enhanced by integrating existing tools, such as decision matrices, with new methods developed specifically to address each bias. The relevance and efficacy of such a methodology will still need to be evaluated and tested for validation.

Future work should investigate how to incorporate metacognition into designers' education, enabling them to better understand their own reasoning process and vulnerabilities. By developing metacognitive skills, designers may become more aware of the existence of cognitive biases and be better equipped to mitigate their impact during the design process. Furthermore, understanding the decision-making process of designers can help in the development of new decision support systems centered on human needs. Finally, future research should integrate the cognitive biases that affect both designers and users of designed products or systems and pursue the development and testing of comprehensive bias mitigation tool methods tailored to each of these roles. Understanding the biases that can influence operators, for example, could enable designers to leverage this knowledge and guide users toward safe behaviors.

References

[1] D. Kahneman, P. Slovic, and A. Tversky, *Judgment Under Uncertainty: Heuristics and Biases*. Cambridge University Press, 1982.
[2] D. Kahneman, *Thinking, Fast ans Slow*. Farrar, Straus and Giroux, 2011.
[3] P. M. Todd and G. Gigerenzer, 'Précis of *Simple heuristics that make us smart*', *Behav Brain Sci*, vol. 23, no. 5, pp. 727–741, Oct. 2000, doi: 10.1017/S0140525X00003447.
[4] C. L. MacLean, 'Cognitive bias in workplace investigation: Problems, perspectives and proposed solutions', *Applied Ergonomics*, vol. 105, p. 103860, Nov. 2022, doi: 10.1016/j.apergo.2022.103860.
[5] I. E. Dror, 'Cognitive and Human Factors in Expert Decision Making: Six Fallacies and the Eight Sources of Bias', *Anal. Chem.*, vol. 92, no. 12, pp. 7998–8004, Jun. 2020, doi: 10.1021/acs.analchem.0c00704.
[6] K. E. Stanovich and R. F. West, 'On the relative independence of thinking biases and cognitive ability', *Journal of Personality and Social Psychology*, vol. 94, pp. 672–695, 2008, doi: 10.1037/0022-3514.94.4.672.
[7] D. Kahneman, 'Maps of Bounded Rationality: a perspective on intuitive judgment and choice', 2002.
[8] A. Tang, 'Software designers, are you biased?', *Proceedings - International Conference on Software Engineering*, May 2011, doi: 10.1145/1988676.1988678.
[9] E. O'Sullivan and S. Schofield, 'Cognitive Bias in Clinical Medicine', *Journal of the Royal College of Physicians of Edinburgh*, vol. 48, no. 3, pp. 225–232, Sep. 2018, doi: 10.4997/jrcpe.2018.306.
[10] G. M. Hallihan, H. Cheong, and L. H. Shu, 'Confirmation and Cognitive Bias in Design Cognition', in *Volume 7: 9th International Conference on Design Education; 24th International Conference on Design Theory and Methodology*, Chicago, Illinois, USA: American Society of Mechanical Engineers, Aug. 2012, pp. 913–924. doi: 10.1115/DETC2012-71258.
[11] U. Kannengiesser and J. S. Gero, 'Design thinking, fast and slow: A framework for Kahneman's dual-system theory in design', *Design Science*, vol. 5, p. e10, ed 2019, doi: 10.1017/dsj.2019.9.
[12] M. H. Bazerman and D. A. Moore, *Judgment in managerial decision making*, 7th ed. Hoboken, NJ: John Wiley & Sons, 2009.
[13] M. Kessler and J. C. Arlinghaus, 'A framework for human-centered production planning and control in smart manufacturing', *Journal of Manufacturing Systems*, vol. 65, pp. 220–232, Oct. 2022, doi: 10.1016/j.jmsy.2022.09.013.
[14] V. K. Viswanathan and J. S. Linsey, 'Role of Sunk Cost in Engineering Idea Generation: An Experimental Investigation', *Journal of Mechanical Design*, vol. 135, no. 121002, Sep. 2013, doi: 10.1115/1.4025290.
[15] R. J. Heuer, *Psychology of Intelligence Analysis*. Center for the Study of Intelligence, 1999.
[16] R. F. Pohl, *Cognitive Illusions: Intriguing Phenomena in Thinking, Judgment, and Memory*. Routledge, 2022.
[17] E. Dimara, S. Franconeri, C. Plaisant, A. Bezerianos, and P. Dragicevic, 'A Task-Based Taxonomy of Cognitive Biases for Information Visualization', *IEEE Trans. Visual. Comput. Graphics*, vol. 26, no. 2, pp. 1413–1432, Feb. 2020, doi: 10.1109/TVCG.2018.2872577.
[18] J. Antony and R. B. Coronado, 'Design for Six Sigma', *Manufacturing Engineer*, vol. 81, no. 1, pp. 24–26, Feb. 2002, doi: 10.1049/me:20020102.
[19] J. C. Gomez Echeverri, 'Cadre méthodologique pour la conception et modélisation des systèmes de production - Intégration des exigences sécurité des opérateurs. Génie des procédés. HESAM Université.' 2021.
[20] N. Cross, 'Design cognition: results from protocol and other empirical studies of design activity', C. Eastman, W. Newstatter, and M. McCracken, Eds., Oxford, UK: Elsevier, 2001, pp. 79–103.
[21] L. Hay, A. H. B. Duffy, C. McTeague, L. M. Pidgeon, T. Vuletic, and M. Grealy, 'Towards a shared ontology: A generic classification of cognitive processes in conceptual design | Design Science | Cambridge Core', 2017.
[22] W. E. Remus and J. E. Kottemann, 'Toward Intelligent Decision Support Systems: An Artificially Intelligent Statistician', *MIS Quarterly*, vol. 10, no. 4, pp. 403–418, 1986.
[23] B. R. LAWSON, 'Cognitive Strategies in Architectural Design', *Ergonomics*, vol. 22, no. 1, pp. 59–68, Jan. 1979, doi: 10.1080/00140137908924589.
[24] J. L. Kolodner and L. M. Wills, 'Powers of observation in creative design', *Design Studies*, vol. 17, no. 4, pp. 385–416, Oct. 1996, doi: 10.1016/S0142-694X(96)00021-X.
[25] D. G. Jansson and S. M. Smith, 'Design fixation', *Design Studies*, vol. 12, no. 1, pp. 3–11, Jan. 1991, doi: 10.1016/0142-694X(91)90003-F.
[26] A. T. Purcell and J. S. Gero, 'Effects of examples on the results of a design activity', *Knowledge-Based Systems*, vol. 5, no. 1, pp. 82–91, Mar. 1992, doi: 10.1016/0950-7051(92)90026-C.
[27] A. T. Purcell, P. Williams, J. S. Gero, and B. Colbron, 'Fixation Effects: Do They Exist in Design Problem Solving?', *Environ Plann B Plann Des*, vol. 20, no. 3, pp. 333–345, Jun. 1993, doi: 10.1068/b200333.
[28] P. G. Rowe, *Design thinking*, 5th print. Cambridge, Mass. London: MIT Press, 1994.
[29] L. J. Ball, J. St. B. T. Evans, and I. Dennis, 'Cognitive processes in engineering design: a longitudinal study', *Ergonomics*, vol. 37, no. 11, pp. 1753–1786, Nov. 1994, doi: 10.1080/00140139408964950.
[30] L. B. Hall-Andersen and O. Broberg, 'Integrating ergonomics into engineering design: The role of objects', *Applied Ergonomics*, vol. 45, no. 3, pp. 647–654, May 2014, doi: 10.1016/j.apergo.2013.09.002.
[31] T. Nelius, M. Eisenmann, M. Doellken, M. Hergl, and S. Matthiesen, 'Improving decision making by teaching debiasing approaches-motivating engineering students with reflection', *Human Behaviour in Design*, pp. 35–46, 2019.