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RESEARCH ARTICLE

Metacognitive Experiences in a Web-Based Cognitive Bias Learning Program: A Study of Collaborative Researchers in Science and Engineering

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Abstract

In contemporary science and engineering, where collaboration has become the norm, researchers' cognitive biases may hinder rational decision-making. This study aimed to develop a web-based learning program to support awareness of cognitive biases in collaborative research contexts and to explore users' experiences of metacognitive reflection. The program was designed around 27 cognitive biases relevant to collaboration and included a self-report diagnostic test, conceptual explanations, and short episode-based four-panel cartoons and video materials reflecting research situations. Ten graduate students and researchers in science and engineering participated in the study, using the program over a period of time and subsequently engaging in semi-structured interviews. The collected data were analyzed qualitatively.

The findings showed that participants used the concept of cognitive bias as a resource for reflecting on their own patterns of thinking and judgment. However, these reflective experiences did not appear in a single or uniform manner; rather, they unfolded in four forms: naming, surfacing, reframing, and reinterpretation. This suggests that the concept of cognitive bias can function as an epistemic resource through which users reinterpret and make sense of their experiences and thinking in diverse ways. Meanwhile, participants' responses indicated a gap between awareness of cognitive biases and actual behavioral change. In addition, reflection on cognitive biases, while meaningful as an individual internal process, appeared to be a dynamic process that can be further expanded through social interaction. This study contributes to understanding how metacognitive reflection on cognitive biases is formed and developed, and offers implications for the design and improvement of debiasing programs for researchers.

Keywords: Cognitive bias, metacognition, collaborative research, web-based learning program, science and engineering researchers

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Introduction

Collaborative research has become a widespread phenomenon in science and engineering (Freeman et al., 2015; Leahey, 2016). Collaboration enables the mobilization of large-scale human and material resources beyond the physical boundaries of time and space, thereby facilitating the advancement of knowledge (Beaver & Rosen, 1979; Wu et al., 2019). The increasing division of labor and specialization within the research process not only contributes to the quantitative expansion of research outputs (Clark & Llorens, 2012; Laband & Tollison, 2000), but also opens up possibilities for addressing novel research problems that were previously inaccessible (Bennett & Gadlin, 2012).

However, collaboration does not necessarily guarantee improvements in research quality (Wu et al., 2019). The micro-level processes of collaboration involve complex and nuanced social interactions. These processes require not only substantial time and material resources, but also cognitive and psychological effort, such as inferring others' intentions and adjusting one's own judgments. In this context, cognitive biases may play a role in undermining researchers' rationality (Hardin, 1998; Janis, 1972; Korteling et al., 2023; Simon, 1990).

Research, as a complex endeavor, requires a high level of rationality and deliberation, involving the long-term examination and evaluation of large amounts of information from multiple perspectives. Therefore, minimizing the influence of cognitive and psychological biases that may undermine intellectual rigor and rational thinking is an important task for researchers. However, cognitive biases are automatic and implicit cognitive processes shaped by the long course of human brain evolution, and prior studies have consistently reported that recognizing and mitigating them is not easy (Croskerry et al., 2013; Korteling et al., 2023; Larrick, 2004; Swaryandini et al., 2025). This suggests that conscious and deliberate interventions or tools are necessary to support the recognition and mitigation of cognitive biases (Larrick, 2004; Rusmana et al., 2020).

Various types of intervention programs aimed at reducing cognitive biases have been developed and implemented across fields such as education and healthcare, and their effectiveness has been reported (Aczel et al., 2015; Rusmana et al., 2020; Swaryandini et al., 2025; Tung & Melchiorre, 2023). Among these, metacognition—defined as higher-order cognitive activity involving the awareness, monitoring, and regulation of one's own thinking processes (Flavell, 1979)—has long been proposed as a key strategy for debiasing (Croskerry, 2003). This is because metacognition can inhibit intuitive modes of thinking and promote more deliberate, analytical, and rational reasoning (Alter et al., 2007; Evans, 2008; Tung & Melchiorre, 2023).

In response, this research team developed a web-based program designed to provide science and engineering researchers with metacognitive experiences related to cognitive errors that may implicitly operate in collaborative research processes. The program was developed as a web-based tool to increase accessibility and to allow individual users to engage with it autonomously. It was implemented with researchers in science and engineering fields over a certain period, followed by one-on-one interviews. The collected data were qualitatively analyzed to examine participants' experiences with the program. Through this process, the study aimed to explore how the web-based program contributed to users' metacognitive reflection, as well as to identify its limitations and suggest directions for future improvement.

Methods

Identification of Biases and Development of Content

The research team reviewed over 180 cognitive biases reported across various fields, including psychology and economics (Ha, 2016). From these, 27 cognitive biases closely related to collaborative contexts were selected and compiled into a list (Table 1). Collaborative settings involve complex interactions among individuals with diverse backgrounds, roles, and contexts. These interactions entail a range of cognitive activities, such as evaluating others' opinions, exchanging perspectives within and across groups, and arriving at shared decisions. In such contexts, multiple cognitive biases may come into play. For example, biases such as conformity bias, authority bias, and in-group bias may hinder the expression of diverse perspectives or the critical evaluation of ideas in group decision-making processes. In addition, if individuals strongly exhibit biases such as social comparison bias or illusory superiority, they may adopt overly defensive attitudes during interactions or have difficulty accepting valid criticism or perspectives from others.

Table 1. List of cognitive biases identified in the context of collaborative research

List of biases	Description
Anchoring Bias	During meetings, the opinion presented first tends to strongly influence the final decision.
Availability Heuristic	Research topics that are frequently mentioned in the media or by colleagues tend to be perceived as important.
Illusion of Validity	In meetings, the opinions of people who present their views consistently tend to appear more convincing or valid.
Conformity bias	Even when my thoughts differ, I feel more comfortable making choices similar to those of my colleagues.
Authority bias	I tend to trust and follow the opinions of people who are more expert than I am (e.g., professors or specialists).
False consensus effect	I tend to assume that many people will agree with the opinions I express.
Reactive devaluation	I tend to trust statements more when they come from someone I view favorably.
Social comparison bias	I feel uncomfortable when I am surrounded by people who appear more capable than I am.
In-group Bias	I consider the opinions of members of my own team more important than those of people from other teams.
Shared information bias	During meetings, information that is familiar to everyone tends to be discussed more than information known by only a few members.
Zero-sum heuristic	In collaborative research, I hesitate to share my expertise because it may put me at a disadvantage.
Halo effect	If someone performs well in one task, I tend to assume that they will perform well in other tasks as well.
Self-serving bias	When outcomes are positive, I attribute them to my own contribution; when outcomes are negative, I tend to blame others.
Just-world Hypothesis	I believe that it is natural for people to receive rewards in proportion to the effort they put in.
Sunk cost fallacy	Even when I realize that my research direction is wrong, it is difficult to abandon what I have already invested and start over.
Egocentric bias	Compared with others, I tend to feel that the tasks I am responsible for are more difficult or demanding.
Optimism Bias	I tend to believe that the work I am doing will turn out well.
Status Quo Bias	Unless there is a clear benefit, I prefer maintaining the current situation rather than trying something new.
Confirmation Bias	Examples that support my ideas are easy to notice, whereas examples that contradict them tend to be overlooked.
Conservatism	Even when new evidence is presented, it is difficult to revise existing beliefs.
Illusory superiority	People tend to believe that their research ability is above average compared with others.
Loss Aversion	I prefer minimizing losses rather than taking risks and pursuing potentially greater gains.
IKEA effect	I place particularly high value on outcomes that I achieved through my own time and effort.
Curse of knowledge	I assume that others understand what I know and therefore do not explain things in detail.
Illusion of Control	When collaborating with colleagues, I tend to believe that the ideas I propose strongly influence the direction or pace of discussion.
Defensive Bias	When someone challenges my opinion during a meeting, I tend to defend it immediately.
Fundamental Attribution Error	When a team member makes a mistake, I tend to attribute it to their responsibility rather than viewing it as a learning opportunity.

For each of the selected cognitive biases, content was developed for inclusion in the program. The program was designed to enable users to naturally connect the content with their own research experiences and contexts. To this end, concrete and intuitive episodic scenarios were created to illustrate how each cognitive bias might operate in collaborative research settings. These scenarios were produced in the form of four-panel cartoons or short videos of less than one minute in length. In addition, to support users' conceptual understanding of each bias, brief explanatory videos of approximately one minute were also developed.

Each learning material was differentiated according to the characteristics of the target bias. Explanatory videos focused on the definition and cognitive mechanisms of individual biases, whereas episodic four-panel cartoons presented distinct collaborative research situations in which the corresponding bias could emerge. The episodic materials were designed to depict realistic situations that researchers could plausibly encounter during collaborative research processes, such as interpreting research papers, discussing experimental results, or interacting with collaborators. For example, authority bias content portrayed a situation in which a researcher questioned the interpretation of a paper but ultimately deferred to the opinion of a well-known professor. Self-serving bias content illustrated situations in which researchers attributed successful collaborative outcomes to their own contributions while attributing negative outcomes to others. Through this design, users were encouraged to connect abstract bias concepts with realistic experiences in research collaboration. The content scenarios were designed by the research team, and the cartoons and videos were produced using generative AI tools, including ChatGPT, Pictory, and Kling.

Program Development

The program was developed as a web-based platform to enable research participants to access and use it easily in their daily lives without temporal or spatial constraints. It was designed to function seamlessly across both PC and mobile environments. The front-end was implemented using Lovable for code generation and development, and the service was deployed via Vercel. User data were stored and managed using Supabase.

Program Structure

The program consisted of two main components: a bias diagnostic test and learning materials (Fig. 1A). After registering and logging in using their existing email addresses, users were able to complete a diagnostic test comprising 30 items (Fig. 1B). Each item was presented as a single statement describing a specific pattern of thinking that may arise in collaborative situations, with one to two items corresponding to each cognitive bias. Users indicated their level of agreement with each statement on a five-point Likert scale. Upon completion and submission of the test, users were provided with a personalized list of cognitive biases based on their responses, along with access to corresponding learning materials for each identified bias (Fig. 1C). The learning materials consisted of two types for each cognitive bias: episodic content and explanatory content (Fig. 1D). While the overall structure of the learning materials was consistent across biases, the specific explanations and collaborative research scenarios differed depending on the characteristics of each cognitive bias. In addition, the diagnostic test could be retaken at any time at the user's discretion, and the list of cognitive biases was dynamically updated based on the new responses.

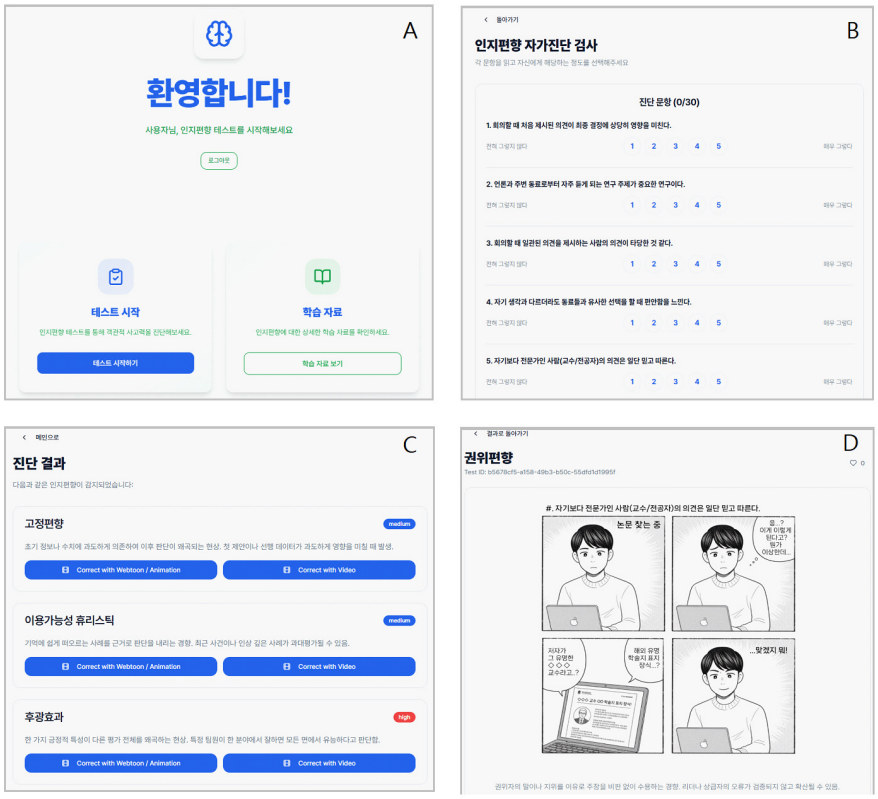

Fig. 1. Screenshot of web-based program. (A) Main dashboard after login. (B) Diagnostic test page. (C) Diagnostic results page. (D) Example of learning content for a cognitive bias (episodic four-panel cartoon).

Program Implementation and Analysis of User Experience

Participants

Participant recruitment was conducted after obtaining approval from the Institutional Review Board (IRB) of the affiliated institution (IRB No. 2511/003-024). In December 2025, participants were recruited from among graduate students and researchers in science and engineering fields who had experience with collaborative research. Recruitment was primarily conducted through the research team's personal networks and was subsequently expanded using a snowball sampling approach based on participant referrals. A total of 10 participants with diverse research fields and varying levels of research experience were ultimately included in the study (Table 2).

Table 2. Participant characteristics

Participant code	Gender	Research field	Research experience (years)	Academic status
R01	Male	Urban Engineering	0.5	Master's program
R02	Male	Physics	1.5	Master's program
R03	Male	Geotechnical Engineering	1.5	Master's program
R04	F emale	Chemistry	2	Master's degree
R05	Male	Physics	2	Master's degree
R06	Male	Computer Engineering	4.5	PhD program
R07	Male	Earth Sciences	5.5	PhD program
R08	Male	Animal Biotechnology	9	PhD completed
R09	Male	Molecular Biology	10+	Research institute
R10	F emale	Population Genetics	11	Research institute

Data Collection and Analysis

Participants in science and engineering fields who voluntarily agreed to take part in the study were provided with a link to the developed web-based program along with usage guidelines, and were instructed to use the program autonomously over a period of three to seven days. Following this period, semi-structured interviews of approximately one hour were conducted with each participant based on a predefined interview protocol, and all interviews were audio-recorded. The recorded audio data were transcribed into text and used for subsequent analysis.

The transcribed data were qualitatively analyzed using ATLAS.ti Web (version 8.7.0). The first author repeatedly reviewed the transcripts to inductively derive key themes and developed an initial codebook based on these themes. The initial codebook consisted of three categories: participants' research experiences, their responses to the web-based program, and their suggestions for program improvement. Subsequently, the first author and three co-authors conducted coding by dividing a portion of the data based on the initial codebook. Through research team meetings, the coding results were compared and reviewed, and discrepancies in interpretation were discussed and reconciled to establish a consensus-based coding scheme.

During this process, the research team recognized the need for a more refined analysis, particularly within the category of "responses to the program." Accordingly, this category was further subdivided into three subcategories—emotional responses, cognitive responses, and value judgments—and the codebook was revised, followed by recoding of the relevant excerpts. Through the second round of coding and subsequent discussions, the need emerged to more deeply examine the epistemic meanings constructed through participants' experiences with the web-based program, particularly in relation to their understanding of cognitive biases. To this end, relevant quotes were selected for each participant, and additional analyses were conducted focusing on their perceptions of cognitive biases and patterns of metacognition. The detailed results of this analysis are presented in the following section. When directly quoting participants' statements, minor revisions were made and the excerpts were translated into English, provided that the original meaning was preserved.

Results and Discussion

Experiences of Metacognitive Reflection

Most participants in this study reported that encountering content focused on cognitive biases was itself unfamiliar. In particular, R10, an experienced researcher who had worked for over ten years in a genetic engineering company, noted that although they had considered themselves to regularly engage in self-reflection, this was the first time they had reflected on cognitive biases that may arise in research or work contexts.

In addition, although the extent varied across participants, most did not merely consume the program content as information or entertainment. Rather, they connected the conceptual language of cognitive bias learned through the program with their concrete and practical experiences of collaborative research. This suggests that the program functioned as a mediating resource that participants could use to reflect on, explain, and make sense of their own experiences.

However, when interpreting these findings, it is important to clarify the nature of the data analyzed in this study. The data were not obtained by observing or measuring participants' thinking processes in real time while they were using the program. Rather, they consisted of retrospective accounts provided by participants during interviews conducted after their use of the program. Therefore, the metacognitive reflection discussed in this study should not be understood simply as momentary cognitive events that occurred at a specific point during program use. Participants' accounts may have been shaped not only by the program itself, but also by the broader context of research participation, the interview situation, and their interaction with the researcher. Accordingly, the experiences of metacognitive reflection examined in this study should be understood as reflective experiences constructed through a continuous process in which participants encountered the topic of cognitive bias, used the program, and later revisited and made sense of their thinking tendencies and past experiences during interviews with the researcher.

These experiences of metacognitive reflection were not confined to a particular stage of the program but were reported at multiple points of engagement. Participants stated that they reflected on their own thinking at different stages, such as while reading the diagnostic test items (R04, R08), reviewing the diagnostic results (R02, R03, R06, R08), and engaging with the episode-based content presented in the form of cartoons and videos (R02, R03, R04, R05, R07, R09, R10). This suggests that the various components of the program did not operate in the same way for all users, but rather served as different opportunities for connecting the concept of cognitive bias with their own experiences. In other words, the program's multiple representational formats and procedural stages can be understood as providing multiple entry points through which users could regard their own thinking as an object of reflection. Therefore, this design can be understood as a resource that helps users with different contexts and dispositions approach reflection in their own ways.

Diverse Patterns and Processes of Cognitive Bias Awareness

Participants' pre-existing cognitive representations of their own thinking tendencies and self-understanding interacted in various ways with the new knowledge encountered through the program, leading to the reconstruction of meaning. As described in the previous section, participants commonly experienced metacognitive reflection in which they came to regard their own thinking as an object of reflection; however, the ways in which these experiences were interpreted and made meaningful were not consistent. Accordingly, this study categorizes these variations into four types—naming, surfacing, reframing, and reinterpretation—and presents the conceptual meaning and representative examples of each type in Table 3.

Table 3. Conceptual meanings and representative examples of cognitive bias awareness patterns

Awareness pattern	Conceptual meaning	Representative examples
Naming	The process of explaining previously vague thinking tendencies through the conceptual language of "cognitive bias."	• R05 stated that "I often have these kinds of thoughts, but I was able to explain them using new terms." • R04 recognized that their cognition could be described through specific terminology. • R02 reported that thoughts they had previously held only vaguely became clearer once they were expressed in words.
Surfacing	The process by which previously unrecognized or implicitly operating thinking tendencies come into conscious awareness.	• R10 newly recognized that they might also show certain biases during research. • R02 reported that they realized the presence of a particular tendency only after encountering the content. • R04 became aware that they had unconsciously held certain patterns of thought.
Reframing	The process of reconsidering thinking tendencies previously understood as personality traits or personal dispositions from the perspective of cognitive error or modifiable cognition.	• R01 stated that they were surprised to see what they had considered a personality trait described as a bias. • R10 recognized that their tendency to think positively, although generally considered a strength, could be problematic in research contexts.
Reinterp retation	The process of using newly acquired cognitive bias concepts as interpretive lenses to reconstruct the meaning of past experiences or collaborative research experiences.	• R09 recognized the possibility that their past adherence to a particular experimental approach may have been influenced by cognitive bias. • R10 reported recalling their patterns of thinking from the early stages of their research career to the present. • R07 recognized that optimism bias could function positively in sustaining research but negatively in administrative checking.

Naming

Naming refers to the process of defining one's specific thinking tendencies or judgment processes using newly acquired conceptual labels. Through the program, participants were introduced to the concept and terminology of cognitive bias and learned concrete situations and cases to which these concepts could be applied. They then recalled their own personal and specific experiences and applied the concept of cognitive bias to these experiences, assigning them appropriate labels. Through this process of naming, individual experiences, cases, and thinking tendencies became identifiable and were structured into categories that could be articulated and explained.

Responses such as "I often have these kinds of thoughts, but now I can describe them using new terms" (R05) and "So this is how my thinking can be described using these terms" (R04) illustrate the process of naming. The metacognitive experience of naming involves acquiring new linguistic concepts and linking them to one's own concrete experiences or cases. The connections formed between concepts and cases in this process may later function as epistemic resources, enabling individuals to compare, explain, evaluate, and interpret similar situations when they encounter them.

The effects of naming are also evident in statements such as, "Before, I only had these thoughts in mind but couldn't express them in words. But seeing them written out made things much clearer" (R02). R02 reported that even prior to using the program, they had repeatedly received feedback from others regarding certain tendencies in their thinking during collaborative research. Although they had sensed the presence of these tendencies, they lacked a conceptual framework to explain them at the time. Upon encountering the concept of cognitive bias through the program, they recognized its close relevance to their own thinking patterns. By assigning a specific "name" to what had previously been vaguely perceived, they came to understand it more clearly. Furthermore, during the interview, R02 repeatedly

expressed statements such as "How should I change this?", suggesting that through naming, certain thinking tendencies began to be recognized as objects of reflection and potential targets for intervention.

Surfacing

Surfacing refers to the process by which thinking tendencies that were previously not clearly recognized or operated implicitly come to the forefront of conscious awareness. Statements such as "Oh, I might actually think like this while doing research" (R10), "When I saw this, I realized that I actually had this tendency" (R02), and "I came to realize that I had been having these kinds of thoughts without noticing" (R04) clearly illustrate this experience of surfacing. In other words, specific thinking tendencies that had not previously been detected emerged into conscious awareness through engagement with the program. These experiences were often described by participants as moments of "realization," suggesting that surfacing was perceived as a meaningful and noteworthy moment.

The process by which previously unnoticed objects of thought come into conscious awareness can be understood as a reorganization of their position within the cognitive structure. That is, once a previously unattended tendency enters the focus of awareness, it becomes an object of active reflection. While both surfacing and naming involve a clarification of awareness, they differ in their modes of operation. Naming is a cognitive process that organizes a given phenomenon into a definable category through conceptual language, whereas surfacing involves the incorporation of previously unconscious tendencies into the field of awareness, thereby reshaping attentional and perceptual focus. In the interview data, naming tended to be expressed through cognitively oriented terms such as "I came to know" or "I learned," whereas surfacing was often accompanied by affective responses, including recollection of past experiences, regret, and moments of realization.

Importantly, surfacing did not occur at the same level for all participants. For example, statements such as "I had already been thinking this way, but it made me reflect on it again" (R06) and "It reminded me of these thoughts again" (R08) emphasize the reactivation of previously recognized patterns of thinking. While these participants acknowledged that the program prompted them to reflect on their thinking, their experiences differed from surfacing in which implicit tendencies newly enter awareness. This suggests that these two types of experiences are distinct, involving different levels of emotional response and epistemic intensity.

Reframing

The program was structured so that users first completed a self-report diagnostic test and then explored learning materials related to the identified cognitive biases. This format was sometimes experienced in a manner similar to widely known psychological tests or personality-type assessments. In fact, some participants approached the program as a tool for identifying their personal tendencies and compared the diagnostic results with traits they had previously understood as part of their personality. As reflected in statements such as "It felt like it matched my tendencies" (R02) and "That's not really my personality, so I was surprised by the result" (R07), participants tended to interpret the list of cognitive biases presented on the results page by contrasting it with their perceived personality or disposition. In such cases, explanations of cognitive biases functioned as a framework for supplementing or reaffirming existing self-understanding.

In contrast, some participants exhibited a process of reframing, in which thinking patterns they had previously understood as aspects of their personality were reconsidered from the perspective of cognitive bias as a form of cognitive

error. For example, statements such as "I thought it was just my personality, but I was surprised to see it described as a bias" (R01) and "I tend to think positively about everything, but I realized that this may not be appropriate in research contexts" (R10) illustrate a shift from understanding certain thinking tendencies as part of one's identity to reconceptualizing them as cognitive mechanisms.

Although the data from this study do not allow us to determine the extent to which it led to practical changes, this shift is significant in that it enables individuals to view certain thinking tendencies not as fixed personal traits, but as modifiable cognitive processes. When such tendencies are regarded as inherent aspects of one's identity, they are less likely to be problematized as targets for change or improvement. However, when understood as cognitive mechanisms, they become more amenable to reflection and regulation, opening up the possibility for intentional adjustment (Dweck, 2013).

Reinterpretation

Reinterpretation refers to the process of using newly acquired concepts of cognitive bias as an interpretive lens to revisit and rearticulate one's past experiences or cases, thereby reconstructing their meaning. This process often involves a temporal and contextual extension, as participants revisited past experiences based on their current conceptual understanding, or recalled various situations that, while not directly identical to the program's examples, could nonetheless be explained in terms of the relevant cognitive bias.

R09, a researcher currently working in a biotechnology company with a PhD and over ten years of research experience, reflected during the interview on their past tendency to adhere to a particular experimental approach for an extended period while being confident in its validity. At the time, they had regarded their judgment as rational; however, after encountering the concept of cognitive bias, they came to recognize the possibility that specific cognitive tendencies had been at play. As R09 stated, "When I was younger, I used to think that way··· but now that I reflect on it, it seems my thinking wasn't always entirely correct," demonstrating a reinterpretation of their thinking patterns and a reconstruction of meaning from a new perspective. Similarly, R10, who also had over ten years of research experience, reported that they revisited their long-term research practices. They noted, "I started to recall my patterns of thinking in research from a very early stage up to now," explaining that ways of thinking developed over time began to be reinterpreted within the framework of cognitive bias.

R07 recognized that "optimism bias" could function positively in sustaining research efforts but might have negative consequences when reviewing administrative procedures. By understanding that the same bias can operate differently depending on the situation and context, they reflectively reconsidered their own stance.

In this way, reinterpretation emerged as a process in which participants revisited their past experiences or different domains of activity and reconstructed their meaning. This suggests that the concept of cognitive bias extended beyond the examples provided in the program and began to function as a new epistemic framework through which participants could interpret their own judgments and experiences.

The Awareness-Action Gap

The experiences of metacognitive reflection reported after program use appeared in the ways participants described and interpreted their pre-existing thinking tendencies and self-understanding in new ways. Although this was a small-scale qualitative study involving ten participants, the ways in which participants made sense of their own thinking tendencies, as well as the intensity with which they experienced such reflection, varied across individuals.

The findings of this study suggest that metacognitive awareness of cognitive biases can serve as an opportunity for individuals to re-examine their own thinking and explore the possibility of future adjustment. However, because the data in this study are based on interview accounts collected after program use, it was not possible to directly determine whether such awareness led to changes in judgment or behavior in actual situations. Some participants reported that, through the program, they came to recognize their cognitive biases as problematic, yet felt uncertain about how to address or change them moving forward. Others expressed an intention to improve but provided limited references to concrete action plans or practical strategies. In response to questions regarding program improvement, several participants highlighted the need for more concrete strategies or guidelines for mitigating cognitive biases, as well as supportive features that could help them continuously monitor and reflect on their thinking tendencies.

These responses indicate the existence of a gap between recognizing cognitive biases and actually regulating one's thinking or changing behavior. Such a gap has been repeatedly highlighted in prior debiasing research (Croskerry et al., 2013; Larrick, 2004; Tung & Melchiorre, 2023). Because cognitive biases are deeply embedded in individuals' cognitive processes, recognizing them is itself challenging. Moreover, even after recognition, the absence of appropriate mitigation strategies or the tendency to maintain existing patterns of thinking often prevents this awareness from translating into actual change (Larrick, 2004). In other words, awareness of cognitive biases may be a necessary condition for behavioral change, but it is not a sufficient one.

In this context, debiasing, in its practical sense, should be understood not as a single event but as a multi-stage process (Croskerry et al., 2013; Rusmana et al., 2020), which calls for a more long-term and structurally oriented approach. Given that most participants in this study were not familiar with the concept of cognitive bias, the concepts and examples provided in the program appear to have served as new conceptual resources for reflecting on their own thinking. This, in turn, served as an opportunity for participants to articulate and reflect on their own thinking. However, if such initial experiences of awareness are not repeatedly reinforced from a long-term perspective, they are likely to remain as one-time insights or may even fade as individuals revert to long-established patterns of thinking.

For the program to have greater practical value, further design is needed to support science and engineering researchers in reflecting on and adjusting their judgments and decision-making during collaborative research. For example, features that visually present individual cognitive bias profiles and record and track changes in awareness and responses over time could provide users with reflective materials that they can continually refer to when examining their own thinking tendencies. In addition, as one participant suggested, linking the program to research notes could help users recall and examine cognitive biases in the course of conducting actual research. Future studies should longitudinally examine how such design improvements influence users' awareness, reflection, and judgment adjustment, as well as how they are related to changes in actual collaborative contexts.

In addition, the four forms of reflection identified in this study—naming, surfacing, reframing, and reinterpretation—can serve as concrete guidance for improving future program design. For example, to support naming, the program could provide a self-recording function that allows users to connect their own experiences with relevant cognitive bias concepts and document them. To support surfacing, self-check questions such as "Have I made a similar judgment in a recent meeting or collaborative research process?" could be used to help users recall thinking tendencies that they do not usually problematize within concrete situations. To promote reframing, learning materials could provide concrete examples that distinguish between personal traits or dispositions and cognitive biases, while also illustrating how such tendencies may be examined and adjusted depending on the situation. Finally, to support reinterpretation, the program could offer activities in which users revisit past collaborative experiences or decision-making cases through the lens of cognitive bias concepts and compare their judgments at the time with their current interpretations. These design improvements may help cognitive bias learning move beyond one-time conceptual understanding and develop into an ongoing reflective process connected to users' actual research experiences.

Extending Reflection through Social Interaction

The program developed in this study was primarily designed to promote individual, internal reflection by supporting users in recognizing and examining cognitive biases. However, through the data analysis process, the research team came to recognize the need to understand the process of cognitive bias awareness not merely as an individual cognitive activity, but as a social process that can be extended and reconstructed through interaction with others. For example, R07 initially recalled only instances in which optimism bias had functioned positively in their research process while using the program. However, during the post-use interview, through dialogue with the researcher, they repeatedly emphasized that they came to newly recognize cases in which optimism bias had operated negatively in specific contexts. This suggests that social interactions—such as dialogue, question-and-answer exchanges, and the sharing of experiences following program use—can mediate the qualitative expansion of individuals' understanding of cognitive biases.

Prior research has likewise argued that there are fundamental limitations to individuals' ability to voluntarily correct their own cognitive biases, and that such efforts need to be supplemented through social, cultural, and institutional supports (Croskerry et al., 2013; Larrick, 2004). From this perspective, the design of the program should take into account how users' experiences with the program may be extended and shaped within their social contexts and networks. For instance, within the program, features that allow users to anonymously share their experiences and respond to others could be introduced, thereby naturally eliciting affective responses such as empathy and promoting the transfer of cognitive bias concepts across diverse situations and contexts. Beyond the program itself, it may also be valuable to consider implementing the program at the level of collaborative research teams, using it as a basis for reflective dialogue and for examining patterns of communication and decision-making within the group. In this regard, the program could play a role in facilitating reflective dialogue among users by providing prompts or guidelines that support safe and productive interaction.

Conclusions and Implications

This study developed a web-based program designed to support science and engineering researchers in recognizing, learning about, and reflecting on cognitive biases, and analyzed users' experiences with the program. The program connected the abstract concept of cognitive bias to concrete episodes drawn from collaborative research contexts, presenting them in the form of short web-based cartoons and videos. It was also designed to be easily accessible in researchers' daily routines and to facilitate natural application and reflection.

Analysis of users' experiences indicated that engagement with the program provided participants with opportunities to reflect on their own thinking tendencies and interpret their experiences through the concept of cognitive bias. These metacognitive experiences did not unfold in a linear or uniform manner; rather, they manifested in diverse forms, including naming, surfacing, reframing, and reinterpretation. This aligns with Merkebu et al.'s (2024) view of metacognitive reflection as a process of observing and examining one's own thinking and experiences and reconceptualizing them from new perspectives. From this perspective, the effects of a cognitive bias learning program need to be conceptualized as including not only users' understanding of the concepts they have learned, but also the reflective process through which they revisit and interpret their own thinking and experiences through those concepts.

However, as a qualitative exploratory study based on a small number of participants, this research has limitations in generalizing the findings or providing quantitative evidence of the program's effectiveness. In addition, the participants in this study were researchers working in science and engineering fields in South Korea, and their experiences should be understood within the context of Korean research culture and collaborative structures. Many of the participants were graduate students or early-career researchers who occupied relatively low-status positions with limited authority within collaborative decision-making structures. This positionality may have influenced how they recognized, expressed, and attempted to regulate cognitive biases. Accordingly, the findings of this study should be interpreted as experiences shaped within a specific institutional and cultural context, and further research is needed to explore the relationship between such contextual factors and patterns of cognitive bias awareness.

Furthermore, because this study focused on participants' immediate experiences and processes of meaning-making following program use, it was not possible to determine whether these metacognitive insights led to actual bias mitigation or long-term behavioral change. Recent debiasing research has also argued that awareness of biases or conceptual learning alone does not guarantee stable changes in judgment, and that structured strategies, repeated practice, and the possibility of transfer to specific contexts need to be considered together (Heerma van Voss et al., 2025; Ko et al., 2025; Swaryandini et al., 2025; Tung & Melchiorre, 2023). In addition, Banner et al. (2026), who examined self-reflection among professionals, showed that self-reflection is not an automatic process, but a complex one shaped by both useful metacognitive strategies and psychological barriers. This suggests that cognitive bias learning programs for science and engineering researchers also need to provide structured reflective environments in which users can safely examine and interpret their own judgments and thinking tendencies.

In this regard, Yazici and Dogan's (2025) study offers useful implications for the present study by showing how metacognitive interventions can be concretely implemented in open-ended problem-solving contexts such as design learning. Design and research share a similar task structure in that both involve dealing with uncertain problems,

generating ideas, evaluating alternatives, and repeatedly revising judgments. In this respect, cognitive bias learning programs for researchers need to include structured reflective procedures that allow users to record their judgments during actual research processes, examine possible biases in advance, and review their judgment processes together with peers. Future research should track long-term user experiences across a more diverse range of participants and examine how these experiences relate to changes in decision-making, adjustments in interactional practices, and transformations in collaborative research culture.

For such program designs to achieve meaningful practical and educational impact, cognitive biases must be handled with care so that they are not reduced to individual deficiencies or personal responsibility. Approaches that attribute cognitive biases solely to individual shortcomings may provoke defensive responses among users, thereby inhibiting reflection and learning. Cognitive biases are a universal feature of human thinking, and this program should function not as a tool for evaluating or selecting individuals, but as a reflective medium that supports understanding one's own and others' thinking tendencies and fosters a more mature culture of collaborative research.

Recent research on bias mitigation has also expanded its focus from individual cognitive training to the design of decision environments, information representations, communication flows, and organizational procedures (Dharanikota et al., 2025; Fasolo et al., 2025; Meguerdichian et al., 2024). In particular, technological debiasing research from a distributed cognition perspective emphasizes that bias mitigation should not rely solely on individual willpower or attention, but should be supported through the design of information flows and decision-making environments (Dharanikota et al., 2025). Meguerdichian et al. (2024) further suggest that reflective dialogue itself may be influenced by cognitive biases, indicating that productive team-based reflection requires prompts, facilitation guidelines, and bias-checking procedures that support safe conversations.

From this perspective, the use of the program should not be limited to individual self-monitoring, but should be extended to collective discussions about how decision-making structures and interactional cultures may contribute to the amplification or mitigation of biases. In this sense, the exploration of debiasing strategies and their effects should be considered alongside broader questions of how to cultivate reflective, safe, and deliberative research environments and structures.

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Conflicts of Interest

The authors declared no conflicts of interest.

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