The role of intellectual humility in promoting epistemic fluency for interdisciplinary engineering education

Kishore Sivakumar* and Mieke Boon

Department of Philosophy, Faculty of Behavioural, Management and Social Sciences, University of Twente, Enschede, Netherlands

Interdisciplinary engineering education aims to equip engineers with the ability to tackle complex real-world problems that occur beyond traditional disciplinary boundaries, therefore demanding a set of interdisciplinary competencies. In our research on interdisciplinary competence, a study consisting of interviews with teachers and researchers focusing on Higher Order Thinking Skills (HOTS) necessary for interdisciplinary research purposes, revealed that the interviewees emphasize specific attitudinal aspects as important for being competent in interdisciplinary research contexts. Notably, the attitudinal aspects as described by the interviewees can be understood through the notion of intellectual humility (IH). This observation motivated an exploratory literature review, which led to the conceptualization of IH as an attitude consisting of the ability to recognize one's intellectual limitations and openness to alternative perspectives and clarified its potential role in the development of epistemic fluency, as an interdisciplinary competence that integrates knowledge, skills and attitude. The refined conceptual understanding of IH along with the empirical findings on the importance of IH resulting from the interviews with experts in interdisciplinary engineering education, supports the view of IH as a crucial attitude for epistemic fluency in interdisciplinary education contexts, together with the importance of awareness and knowledge of disciplinary perspectives. Epistemic fluency, in turn, is conceptualized as a key interdisciplinary competency that integrates knowledge (disciplinary perspectives), attitudes (IH), and skills (HOTS). Finally, suggestions are made for possible ways to promote IH as part of this competence.

KEYWORDS

intellectual humility, epistemic fluency, higher order thinking skills, competence, interdisciplinary engineering education, attitude

1 Introduction

The significance of interdisciplinary research approaches, especially in addressing the unprecedented real-world challenges characterized by complexity, uncertainty, and wickedness, has been widely emphasized (Meijers and Den Brok, 2013; Gómez Puente et al., 2015). In recent decades, education institutions have been adopting inter and transdisciplinary educational frameworks such as problem-based learning and challenge-based learning to support the development of interdisciplinary competencies in addition to traditional domain-specific competencies (Spelt et al., 2017; Lattuca et al., 2017; Van den Beemt et al., 2020; Routhe et al., 2023).

When approaching interdisciplinarity from the perspective of learning outcomes, Spelt et al. (2009) prioritize the process of integrating disciplinary insights as a defining feature of interdisciplinarity. They argue for integrative thinking as a key learning objective to enable

students to carry out interdisciplinary research. This aligns with Boix Mansilla's (2016) definition of interdisciplinarity as the "integration of knowledge and modes of thinking in one or more disciplines in search for better understanding." Similarly, Menken and Keestra (2016), highlight the ability to combine diverse academic perspectives, as a key learning objective in interdisciplinary research education. In the context of interdisciplinary learning objectives, above cited accounts underscore the importance of the ability to integrate knowledge and perspectives from different disciplines, an ability that can be understood as a Higher-Order Thinking Skill (HOTS). The term HOTS encompasses complex cognitive processes that go beyond the basic process of recalling or recognizing information (Cuban, 1984; Resnick, 1987; Lewis and Smith, 1993). Cognitive functions that involve analysis, evaluation, and creation are typically classified as higher order, as they require complex and non-linear thinking processes, utilizing multiple types of knowledge (Bloom, 1956; Anderson and Krathwohl, 2001).

1.1 Epistemic fluency

1.1.1 Epistemic fluency as HOTS

Epistemic fluency (EF) can be understood as a HOTS crucial to interdisciplinarity as a learning outcome, as it involves the ability to *integrate* knowledge and perspectives across different domains.[1] Morrison and Collins (1995) define EF as the ability to engage in various epistemic games, i.e., processes involving specific rules, tools, and methods for acquiring knowledge. They emphasize the importance of understanding and utilizing different methods of knowledge construction and associated expression and evaluation, thereby fostering empathy with individuals operating within alternative epistemic frameworks (Morrison and Collins, 1995). Building upon this foundation, Markauskaite and Goodyear (2017) highlighted the importance of proficiency in integrating and applying diverse perspectives in knowledge construction. *"It entails a deep understanding of how knowledge works, the capacity to participate in the creation of actionable knowledge, and a sense of how to reconfigure the world to see what matters more clearly and enable oneself, and others, to act more knowledgeably"* (Markauskaite and Goodyear, 2017, p. 20).

This account of EF as HOTS aligns well as a learning goal in interdisciplinary education context,[2] particularly with regard to generating knowledge to address complex real-world problems through understanding the interactions of different elements of a system/phenomenon at the intersection of multiple disciplines. Grounding in this description of EF as an interdisciplinary learning goal involves epistemological insights into the role of disciplinary perspectives, according to which a disciplinary perspective is the means by which knowledge is constructed within a discipline. It encompasses the concepts, theories, approaches, methods, and tools that form the foundation of that discipline for generating knowledge (Boon, 2020). In other words, a disciplinary perspective can be understood as a lens through which the phenomena typically studied in that discipline are perceived, using the concepts and measurement instruments typical to the discipline, and then theoretically interpreted or explained in a way that is meaningful and understandable within the discipline.

1.1.2 Epistemic fluency as a competence

To translate these valuable epistemological insights into pedagogical applications, the HOTS framework can situate EF as a cognitive learning goal, one of the important abilities to integrate knowledge from different disciplines (and thus to substantiate interdisciplinarity as a learning goal). However, the HOTS framework does not provide sufficient insight about how to promote EF. The competency[3] framework by Baartman and De Bruijn (2011), offers a holistic approach to understanding skill related learning objectives, garnering attention to the knowledge and attitude[4] aspects of a competence. Therefore, in this paper, we approach EF as a competence which could help understand the competence better in terms of skill, knowledge and attitude constituents thus potentially contributing to promote EF in interdisciplinary educational contexts.

1.1.3 Relevance of intellectual humility

One such attitude, which may play a role in promoting EF, is *intellectual humility* (IH). Broadly, IH represents the attitude that no one epistemic approach is complete or infallible on a given subject matter, including the approach one is trained or specialized in, and that one should at least be open to alternatives that may have value within a given domain (Leary et al., 2017). Therefore, we will argue that fostering an attitude of IH is an important part of promoting EF.

To substantiate this concept, we draw on the role that scholars and experts in interdisciplinary education attribute to IH and how it can

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be achieved or cultivated among students. To this end, we use the results of a broader study of HOTS within interdisciplinary engineering education, which includes both a literature review of HOTS and an interview study of interdisciplinary experts. Both the literature and our interview study raise IH as an important attitude or virtue[5] and reflect on its implementation. However, we begin with a brief introduction to the concept of IH as it has been historically characterized, before turning to our study and the consideration of how IH is understood, characterized, and implemented in practical contexts of interdisciplinary education. These theoretical and philosophical insights provide a basis for recognizing and understanding discussions of IH and the potential relevance of IH to developing EF.

1.1.4 Intellectual humility as a virtue and attitude

For the purpose of this article, IH is conceptualized as an attitude. Framing IH as an attitude, rather than a virtue, provides a potentially coherent basis to better understand the underlying cognitive and epistemic aspects that correspond with the competence framework in terms of HOTS, attitude, and knowledge, thereby augmenting the importance of promoting IH, possibly in relation to EF, in interdisciplinary educational settings.

2 Methods

As mentioned, the findings of this article are part of a larger study that aimed to identify and characterize the HOTS (Higher-Order thinking skills) necessary for interdisciplinary scientific reasoning and problem-solving in academic settings. For this purpose, a qualitative mixed methods approach was employed, consisting of a semi-systematic literature review and semi-structured interviews to investigate scholarly and experts' views on these skills. The interview transcripts were coded and classified using an emergent thematic classification method (Charmaz, 2008). During the data classification process, it became apparent that the experts interviewed emphasized the importance of attitudes and virtues that are crucial for enhancing the effectiveness of HOTS in interdisciplinary collaboration. This finding led to the exploration and conceptualization of the concept of IH as presented in this paper.

2.1 Semi-systematic literature review

Snyder (2019) identifies the semi-systematic approach as a feasible and effective method for reviewing literature with a broad scope. The use of a semi-systematic literature review method allows for flexibility in the data analysis process while still adhering to a rigorous protocol for literature search and selection. The review was conducted with the

objective of gaining a conceptual understanding of various HOTS related to interdisciplinary research practices in higher education. The literature search[6] was conducted using three major databases (ERIC-EBSCO, PsycInfo, and JSTOR) based on relevance, accessibility, and availability factors, and focused on articles written in English and published between 1980 and 2021. A total of 1,053 articles were retrieved, 67 of which were selected after reading the abstracts, and 37 were chosen after full reading. The selection criteria were based on whether the article addressed the concept of HOTS or aspects of HOTS, such as critical thinking, creative thinking, interdisciplinary thinking, etc., from high school to higher educational contexts. Literature specifically related to IH or EF was not part of this larger study. However, after processing the interviews it became strikingly clear that IH and EF were considered important by the interviewees for acquiring those HOTS. Consequently, a follow-up (exploratory) literature review was conducted focusing on IH and EF, as explained in more detail below.

The literature review was completed prior to the analysis of the transcripts, and certain categories of important HOTS had already been identified. Finally, the findings from the literature and interviews were interrelated and merged into a preliminary conceptual framework of HOTS that is relevant to interdisciplinary education contexts.[7]

2.2 Exploratory literature review

In the literature review that identified different categories of important HOTS for interdisciplinary approaches in education, only one of the 37 selected articles specifically addressed the attitudinal aspects of intellectual humility (IH). In the analysis of the interviews that were similarly focused on important HOTS for interdisciplinary approaches, statements emphasizing the aspects of IH emerged significantly: IH-related statements were coded 12 times in the responses of 12 of the 22 respondents in the coding process. Therefore, to further investigate the possible role of this attitude in developing HOTS, an exploratory literature review was conducted in Google Scholar using the search terms 'intellectual humility,' 'open-mindedness,' and 'intellectual virtues.' The primary focus was on exploring the concept of IH from philosophical and psychological perspectives, but without focusing on the role of IH in relation to the development of HOTS in interdisciplinary research. Finally, the general insights on IH were combined with those gathered from the interviewees, to conceptualize IH in the context of interdisciplinary engineering education.

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5   In philosophy, virtues are typically considered desirable traits or qualities that promote ethical or admirable behavior, often carrying a moral dimension to the concept and approaching it as an internal stable trait. In the context of character education, virtues have been conceptualized, informed by psychology, as a character disposition that can be cultivated through practice (Kristjánsson, 2012; Annas, 2016).

6   Key search words were used to retrieve articles from the database that focus on the topics of higher order thinking skills, interdisciplinary research, project-based learning, and engineering education. The search terms were carefully chosen to ensure that the articles retrieved were relevant to the research question and provided valuable insights into the topic. The use of Boolean operators such as AND and OR allowed for the refinement of the search results, ensuring that only the most relevant articles were selected for further analysis. The inclusion of different variations of the term higher order thinking skills (e.g., "Higher order cognitive skills") also helped to capture a broader range of articles on the topic.

7   This conceptual framework of HOTS will be published in a separate paper.

3 Results

Our analysis of the educational and philosophical literature led to a dual conceptualization of themes related to IH in the context of interdisciplinary education. Similar to the analysis of intellectual virtues by Alfano et al. (2017), two major categories emerged. The first category, *Recognizing Intellectual Limitations* (RIL), refers to the ability to acknowledge the boundaries of one's own perspectives and the knowledge that stems from them, especially in an interdisciplinary setting. The second category, *Open-Mindedness* (OM), is recognized as another important aspect of IH in interdisciplinary education, involving the willingness to reconsider one's beliefs and assumptions when confronted with new or competing perspectives.

As mentioned, based on the analyses of the interviews focusing on HOTS in interdisciplinary research, 12 of 22 respondents pointed to the importance of specific attitudes that are crucial for interdisciplinary research and that can be understood as intellectual humility, IH. Importantly, respondents brought up the significance of these attitudes without being explicitly asked about such attitudes. Furthermore, the two different categories characterizing IH found in the literature were also found in the interviews, although not always explicitly using these terms (see Table 1).

In this section, the results are structured around these two categories of IH: Recognising Intellectual Limitations (RIL) and Open-Mindedness (OM), with each section presenting findings from the literature (including definitions or quotes that address the mentioned aspects of IH), and from the interviews (including

exemplary quotes from respondents who explicitly or implicitly argued for either aspect of IH, with relevant context added to these quotes where necessary). It is also worth noting that the literature section contains accounts of IH in general, not specific to interdisciplinary contexts. However, the responses from the interviews highlight some potentially crucial aspects of IH in interdisciplinary contexts. Merging these two sources provides an interpretation of IH that is well-suited for interdisciplinary educational settings.

3.1 Recognizing intellectual limitations

3.1.1 Literature insight

The findings from the literature on the meaning of IH highlight the centrality of recognizing one's intellectual limitations as the defining feature of IH. Tanesini (2018) defines IH as "a psychological quality which is involved in the evaluation of aspects of one's own cognitive agency" highlighting the function of assessing one's cognitive strengths and limitations in a given context. Zmigrod et al. (2019) present IH as a virtue that enables individuals to acknowledge their potential for fallibility when forming and revising their beliefs and attitudes. Similarly, Hopkin et al. (2014) build on Roberts and Wood's (2003) philosophical foundations, describing IH as a "mindset and actions associated with treating one's own views as fallible and an openness to changing or reinterpreting those views faced with superior information." Taking one step further, Whitcomb et al. (2017) argue that "proper attentiveness to, and owning, one's intellectual limitations"

TABLE 1 Overview of the interview data where green blocks indicate experts that highlighted the importance of RIL and OM as an important attitude for interdisciplinarity.

Respondents	Positions (ID stands for Interdisciplinary)	Country of Residence	RIL	OM
Respondent 1	Research Director: ID Research Institute	France	■	
Respondent 2	Program Director: ID Master's program	France		
Respondent 3	Nobel Laureate in Physiology	USA		
Respondent 4	Professor: Nanomaterial Chemistry	Netherlands		■
Respondent 5	Assistant Professor: Engineering Management	Netherlands		■
Respondent 6	Research Director: Immunology Research	France	■	
Respondent 7	Assistant Professor: Communication Science	Netherlands		
Respondent 8	Teacher Trainer: Challenge-Based Learning Expert	Netherlands		
Respondent 9	Educational Consultant	Netherlands		■
Respondent 10	Assistant Professor: Material Science	Netherlands		■
Respondent 11	Senior Lecturer: Geo-informatics	Netherlands		
Respondent 12	Associate Professor: Physics	Netherlands		
Respondent 13	Lecturer: Physics	Netherlands		■
Respondent 14	Lab Director: Electronics and IoT	France	■	
Respondent 15	Teacher Trainer: Challenge-Based Learning	Netherlands		■
Respondent 16	Professor: Cellular Biology	USA		
Respondent 17	Professor: Education Science	Netherlands		■
Respondent 18	Director and Founder: ID Research Institute	France	■	
Respondent 19	Lecturer: Mathematics	Netherlands		
Respondent 20	Lecturer: Social Sciences	Netherlands		
Respondent 21	Educational Consultant	Netherlands		
Respondent 22	Associate Professor: Engineering Technology	Netherlands		■

is the most critical aspect of IH. Finally, Porter et al. (2022) identified the recognition of one's intellectual limitations as a unifying feature across both philosophical and psychological perspectives on IH. Our analysis of the literature makes clear that recognizing one's own intellectual limitation is considered a core feature of IH in both philosophical and psychological conceptualizations.

3.1.2 Respondent insights

In the context of interdisciplinary education, Respondent 6 (R6), the head of an interdisciplinary research group in a renowned laboratory, stated:

> "I think it's also true to say that lots of things, they (students in interdisciplinary settings) do not know, or it is not known, and both are fine, but it's just important to understand the difference between the two and a lot of things aren't known. In fact, that's what you realize as you move on. In science, more things are unknown than are known, and it's good to know that you do not know everything, so it's not a goal to try and foster a sense of humility. But it is to try and understand what they do not know if they do not know something, but they have a basis of understanding of all these different parts."

R6 thus emphasizes the importance of recognizing the distinction between what is known and what is unknown. This response highlights the importance of recognizing one's intellectual limitations as crucial for interdisciplinary practices.

Respondent 14 (R14), a professor from an interdisciplinary engineering research program, noted:

> "For me, the most difficult part, even for researchers, is to find your place in a new problem and also understand that you cannot solve everything by yourself, but still, you can do a little bit of something. And how and what will be the best way to contribute and to go back for it, is for me the most difficult thinking skills I think students need."

R14 thus emphasizes the importance of finding one's role in tackling a new problem and recognizing that it is impossible to solve everything independently, thereby encouraging an awareness of one's role in solving problems including one's strengths and limitations in an interdisciplinary context.

Respondent 1 (R1), the head of a research unit and co-founder of an interdisciplinary research center stated:

> "You also have to be able to zoom out and know the limitations of your knowledge, of your discipline."

> "Accepting that a solution for one person is objectively not a solution for someone [else] depending on his [her] discipline, but being able to understand the significance of that solution in general."

Similarly, R1 indicates the importance of recognizing the limitations of one's knowledge and discipline while acknowledging the different perspectives in a given context.

Respondent 18 (R18), co-founder of an interdisciplinary research center, indicated:

> "But you have to know that no discipline is as intelligent as all disciplines together. So, you have to have this humility. You have to

> be proud of what you know and humble about everything you do not know. You have to be able to argue for your perspective that should be taken into account for the overall understanding of the elephant or the complexity of the problem."

R18's statement thus recognizes the importance of humility and openness while appreciating the value of multiple disciplines working together.

3.1.3 Summary

Insights from the literature suggest that RIL is an important feature of IH in general contexts, while responses from experts emphasize its relevance in relation to interdisciplinary contexts. In particular, RIL is considered an attitude of (i) acknowledging the fallible nature of human reasoning—that is, our perspectives are prone to biases and errors, (ii) recognizing one's own intellectual advantages and limitations, stemming from an awareness of both one's own and others' disciplinary perspectives, (iii) the willingness to reconsider and revise one's beliefs when confronted with new evidence or perspectives, and (iv) humility to admit ignorance or knowledge gaps.

3.2 Open-mindedness

3.2.1 Literature insights

Baehr (2011) defines an open-minded person as "willing and (within limits) able to transcend a default cognitive standpoint to take up or take seriously the merits of a cognitive standpoint," highlighting the importance of being open to and adopting other perspectives when working in interdisciplinary contexts. An expert review on IH by Alfano et al. (2017) identified OM as a crucial component of IH, and Hare (2003) describes open-mindedness as "a kind of critical receptiveness in which our willingness to consider new ideas is guided by our best judgment with respect to the available evidence." Spiegel (2012), reaffirming Hare's account of OM, attempts to substantiate the classification of OM as a subconstruct or prerequisite of IH.

From a practical perspective, Barković (2010) argues that "open-mindedness is critical to effective interdisciplinary studentships; students need to listen to others' perspectives, talk informally with other students, attend a variety [of events], and learn about the foundations of, and follow developments in, contributing disciplines." Along the same lines, Vanney and Sáenz (2022), in the context of interdisciplinary research, argue that "the success of any research activity depends largely, as mentioned in the previous sections, on researchers having developed in themselves a rich array of intellectual virtues, such as open-mindedness, intellectual humility, and intellectual creativity," pointing to the broader intellectual virtues needed for success in interdisciplinary research. It is important to note that Vanney and Sáenz (2022) conceptualize it as a separate intellectual virtue, rather than as an attitudinal aspect of IH.

Respondent Insights: Similarly, interviewees have stressed the importance of OM in interdisciplinary research and education contexts.

Respondent 15 (R15), a teacher trainer for challenge-based learning approaches in higher education, indicated:

> "It [HOTS required for interdisciplinary contexts] has to do something with open-mindedness and being aware that you are thinking or (about) your mindset. It always is not set, but it should be. You should always question your own mindset."

R15's perspective thus emphasizes the importance of maintaining an open and flexible mindset by constantly challenging one's own perspectives and beliefs through questioning.

Respondent 17 (R17), a professor in innovation in higher education, responded:

> *"Referred to me as the social skills [HOTS important for interdisciplinary contexts]. Teamwork, collaborating with people with other cognitive strengths. Communication skills and open communication, openness to each other, [and] willingness to learn from each other, you could say, both conceptually and methodically [in interdisciplinary research]."*

R17 thus insists that being open and having the willingness to learn from others—both conceptually and methodically—when interacting in an interdisciplinary research context, is crucial.

Respondent 5 (R5), an assistant professor in an engineering and management program, stated:

> *"Well, you should be open-minded, right, to try to understand the other perspective."*
>
> *"So, understanding, for example, the theories that are mostly used in different disciplines… being familiar with the concepts, the terminologies you might say, the assumptions and the theories in the different disciplines."*

R5 thus points at the importance of open-mindedness needed for recognizing and understanding others' disciplinary perspectives.

Respondent 9 (R9), an educational consultant, asserted:

> *"I guess you also you need to have flexibility, and you need to be open. That would be a prerequisite because we often come across students saying, oh, that guy from that discipline was not flexible. He would not listen to [him and thinks] his [way] was the best way."*

R9 thus acknowledges OM as a prerequisite in an interdisciplinary research context.

Respondent 22 (R22), an associate professor in engineering technology, said:

> *"But you are aware of those kinds of things that there is a bigger picture out there. And that's why you do your research and what you learn is positioned somewhere in the bigger picture. And that is for me [is important] that you are self-aware about that. You are able to reflect on that. And then you are also able to understand that another person comes from another corner and understand that maybe people have indeed not only diverging but sometimes even competing or contrasting perspectives."*

R22 does not explicitly mention OM as a skill but rather argues for the awareness and recognition of diverging perspectives, which obviously requires being open-minded in an interdisciplinary research context.

Respondent 4 (R4), an established professor in an interdisciplinary engineering group, stated:

> *"To be able to be willing to cross and to be able to try to stand next to the other person, try to see the world from this perspective… to listen to the other person."*

R4 thus highlights that individuals should have the willingness to look at other perspectives, which is a core feature of open-mindedness.

Respondent 13 (R13), a natural science teacher in an interdisciplinary bachelor's program, responded:

> *"Yeah, yeah, I think, this kind of open-mindedness or something that you would need. [It] really helps. I guess if you really are curious to what the other discipline is doing, I think that's the baseline if you want to collaborate with someone from a different discipline. And I mean, you need to kind of be open to learn also…."*

R13 thus puts emphasis on curiosity and the willingness to appreciate other perspectives in interdisciplinary research.

3.2.2 Summary

Both the literature and interviews emphasize the importance of OM in interdisciplinary contexts, highlighting specific features such as: (i) the ability to question one's own perspectives and beliefs, (ii) the recognition that diverging perspectives exist, (iii) the willingness to learn about other disciplinary viewpoints and their underlying assumptions, and (iv) the understanding and appreciation of the role these differing perspectives play in an interdisciplinary setting.

4 Discussion

This section aims to first summarize the findings on IH and then to explore its relevance to EF and interdisciplinary education, thereby providing a rationale for positioning IH as an interdisciplinary learning goal. Specifically, in the context of interdisciplinary competences, drawing from literature and expert responses, EF is conceptualized as a key interdisciplinary competence that integrates knowledge (disciplinary perspectives), attitude (IH), and skills (Higher Order Thinking Skills, HOTS). As a part of the competence construct the relevance of IH as an attitude is argued to be crucial to EF, along with the importance of awareness and knowledge of disciplinary perspectives.

4.1 Intellectual humility

In a nutshell, for the interdisciplinary educational context, based on the insights from this study, it is reasonable to interpret intellectual humility (IH) as a concept that encompasses two key aspects rooted in the awareness of disciplinary perspectives: (i) RIL: the recognition of one's intellectual limitations, i.e., acknowledging that one's knowledge, limited by one's disciplinary perspective, is fallible and subject to revision, and (ii) OM: openness to learning from other disciplinary perspectives.

4.2 Epistemic fluency

As highlighted in the introduction, the definition of EF—as a HOTS that entails the ability to recognize and integrate multiple perspectives and knowledge domains fluently—conceptually positions

IH as a prerequisite attitude that is needed to develop fluency between disciplinary perspectives. In other words, without IH, the development of EF may be limited or poorly formed.

Another important finding of this study is the importance respondents attach to the role of disciplinary perspectives in relation to attitudinal aspects of IH. This highlights the knowledge dimension within the competence construct, prompting the conceptualization of EF as a competence (not just as a HOTS) for interdisciplinary educational contexts. Through this framing and based on the findings of our study, EF can thus be understood as competence comprising three components:

i.   HOTS (higher-order thinking skills): the ability to recognize and integrate multiple perspectives and knowledge domains fluently.
ii. Attitude: IH understood as an attitude including the aspects of (a) RIL: the recognition of one's intellectual limitations, i.e., acknowledging that one's knowledge, limited by one's disciplinary perspective, is fallible and subject to revision, and (b) OM: openness to learning from other disciplinary perspectives.
iii. Knowledge: an awareness and knowledge of multiple scientific disciplinary perspectives (both natural and social sciences), along with knowledge of tools and strategies to understand and integrate different perspectives.

In the general educational context, both RIL (mainly framed as IH) and OM are recognized for their roles in fostering intellectual virtues (Howard-Snyder and Battaly, 2020). Pritchard (2020) argues that effective education should cultivate both aspects of IH, which involves acknowledging one's limitations and convictions, and intellectual self-confidence which refers to holding firm, well-justified beliefs. More specifically, in an interdisciplinary context, Palmer (2023) highlights the importance of IH, which includes aspects of RIL, understood as an inward process of reflective self-evaluation of one's intellectual limitations, and OM, understood as an outward process of engaging and appreciating others' perspectives, particularly when interacting with academic and non-academic knowledge systems.

4.3 Pedagogical strategies

In the context of IH, Palmer (2023) suggests focusing on promoting conducive environments in which researchers feel safe to admit what they do not know, which could lead to constructive dialogues across disciplines. Strategies highlighted include nurturing a culture that values questions and curiosity rather than that seeking just answers, and normalizing uncertainty thus making room for diverse perspectives (Palmer, 2023).

In our interviews, respondents suggested a few pedagogical strategies that they employ to promote HOTS for interdisciplinary contexts, though not explicitly targeting IH. However, some of their strategies may implicitly foster IH.

One of the commonly employed strategies to promote HOTS in an interdisciplinary educational context was put forward, in one or another form by eight out of 22 respondents (see Supplementary information), is interactive questioning sessions with students. Based on the insights expressed by respondents in the interviews, these interactive questioning sessions are characterized by the Socratic method (prompting students to discover answers and assumptions through guiding questions), interactive discussions to identify knowledge gaps, and the creation of a safe learning

environment that encourages open-ended questions and progressive interrogation (moving from simple to complex questions).

Another pedagogical strategy to promote HOTS in a way that also fosters IH as suggested by the interviewees is peer learning. For example, Respondent 1 emphasized the importance of collaborative peer learning, particularly between students from different cultures, languages, and disciplines. Respondent 1 argued that grouping theory-oriented and experiment-oriented students for group activities can foster an understanding of each other's perspectives, which might potentially promote, to a certain degree IH.[8] Along similar lines, Respondent 18 stressed the value of classroom exercises that combine theory and experimentation and argued such exercises encourage adaptability and humility in interdisciplinary learning contexts.[9]

4.4 Leveraging disciplinary perspectives to promote intellectual humility

When it comes to promoting IH and, thereby, potentially developing EF, an important third pillar of EF competency is the awareness and knowledge of disciplinary perspectives. Boon and Van Baalen (2019), Macleod et al. (2019), and Boon (2020) specifically address the role of disciplinary perspectives, offering clarity and valuable insights on the required epistemic

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8 Respondent 1: "The first thing that we try to do is that, you know, that [we] try to never leave a student alone, which means that they always work together with someone else. And ideally not only with a mentor, but in a peer-to-peer situation. And if you get it right, then the peer-to-peer interaction between students that come from different cultures or just different disciplines. So, because they have to work together, they are bound to pass the first language barrier than they discuss, right in order to be able to work together when they understand each other's language. The second thing is you give them a task. In order to be able to deal with this task, right, they need the skill sets of both of them. So, a classic example is you take, you know, an experimental, a savvy student and a theoretical savvy student, and you give them a work to read. That covers both aspects. There was maybe a mathematical model and experimental setup and results. And if you do things even better, you do not give them, you ask them to find such a resource. So, by engaging them to find a common paper (published) meant that both of them are interested in. And that covers their main domains of expertise, which are orthogonal to each other. They are bound to discuss with each other, to share their passions, to share their questions, to share what they are interested in, and to find this paper. This unique paper that unites them."

9 Respondent 18: "I really want students to do experiments and to be able to go back and forth between the two (theories) because the theory helps you with a conceptual vision of the world and some generic understanding. But the experiments can tell you, how wrong you are, and your theory is and will force you to revise your assumption and open to this, red with yellow strikes when you ask black or white or whatever. And so, you have to be able to go back and forth. And again, it's all sort of a humility lesson. But being able to build with your own hand or go make your hands dirty and so on quickly, you realize that what you had in mind, versus reality is very different. So even, you know, mathematicians have come to know how to do experiments and experimentalists have to find a way to understand what's the model with such data. How do you analyze them, and you make sense out of them? And so on...."

underpinnings for an interdisciplinary educational context. Boon (2020) argues that a disciplinary perspective shapes how researchers identify phenomena and construct models, as these perspectives guide the concepts and methods used within a discipline and suggest that making disciplinary perspectives explicit helps in critically assessing models and overcoming subjectivism, especially in interdisciplinary work, where multiple perspectives are at play. Specifically, Boon and Van Baalen (2019) propose conceptual modelling exercises designed to nudge and scaffold students with the goal of understanding real-world problems. Moreover, Van Baalen and Boon (2024) provide a scaffolding framework to systematically analyse the disciplinary perspectives of experts in multi-disciplinary teams collaborating in interdisciplinary research and design projects. Similarly, reflection exercises that include in-class interdisciplinary discussions, such as engaging with a multidisciplinary team to discuss a subject, participating in scientific debates on scientific paradigms, along with completing reflective questionnaires on epistemological beliefs to promote awareness on disciplinary perspectives (Boon and Van Baalen, 2019; Boon et al., 2022). These exercises are designed to encourage students to critically examine and contemplate the role of different disciplinary perspectives in knowledge creation specifically geared toward addressing real-world challenges.

4.5 Limitations

There are some general limitations to the method employed in this study which should be borne in mind: (i) convenience sampling was chosen due to feasibility over random sampling, which could have introduced significant bias, (ii) only 22 experts were included, limiting the diversity in perspectives required to understand interdisciplinary educational strategies, and (iii) while the data analysis was presented and discussed with a set of experts, the authors' involvement in the analysis process may have influence on the synthesis of the results.

4.6 Suggestions for future directions

The identification of RIL and OM aspects of IH provides a basis for designing a targeted interview protocol to explore IH and its role in promoting EF more directly.

i. As a next step, a study involving a broader range of experts, combined with inter-rater reliability standards in data analysis, could enhance the clarity and increase the applicability of EF as a competence within interdisciplinary educational contexts.

ii. While this paper provides the theoretical and empirical base for the conceptualization of EF as a competence, further validation of this conceptualization through implementation, by measuring the development of EF in students, in interdisciplinary educational contexts could strengthen its relevance and applicability. This also implies further research into development of reliable assessment tools to measure the EF as a competence.

iii. Finally, it is observed that only four respondents mentioned RIL, whereas eight respondents highlighted the importance of OM. Aside from the fact that the interview did not specifically

focus on IH-related concepts, this relatively low frequency could stem from a general lack of familiarity with IH concepts, as researchers and teachers may not necessarily have background knowledge in educational psychology or epistemology. It could be worthwhile to investigate the knowledge and awareness of teachers regarding the concepts of IH and EF and its impact on course design and teaching practices in classrooms.

5 Conclusion

This paper presents IH as an important attitude in the context of interdisciplinary engineering education and attempts to provide an appropriate conceptualization of IH. It draws attention to the less apparent but crucial role of awareness of disciplinary perspectives and encourages the development of IH informed by knowledge of these perspectives. In this context, the paper also offers insights from teachers, researchers, and academic sources on pedagogical strategies that could potentially help to promote IH. Finally, we argue that with greater conceptual clarity about IH improves our understanding of its potential to promote EF within interdisciplinary engineering education.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author.

Ethics statement

The studies involving humans were approved by University of Twente, BMS Ethics Committee. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Author contributions

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/feduc.2024.1395265/full#supplementary-material

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