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How do students deal with the uncertainty of sustainability challenges? Metacognitive learning in a transdisciplinary course

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While tackling sustainability challenges, engineering students confront various uncertainties, including the unpredictability of real-world scenarios, unfamiliar aspects of problems, and conflicting viewpoints among stakeholders. Despite previous research indicating the likelihood of encountering such uncertainties in sustainability projects, it is unclear if students are aware of uncertainty and what specific regulatory behaviors they develop to address them. This study seeks to deepen our understanding of the awareness and regulation of uncertainty by students while they work on real-life sustainability challenges. To achieve this, we observed nine MSc students enrolled in a transdisciplinary course on urban sustainability at a Dutch university of technology. Through interviews, we explored the uncertainties they faced and how they navigated them. Our analysis, conducted through open, consensus-based coding by two researchers, revealed that students primarily encountered the uncertainty of multiplicity, characterized by divergent stakeholder perspectives. Additionally, students increasingly recognized the inherent unpredictability of the challenges over the course. To address uncertainty, students developed three kinds of behaviors to deal with uncertainty: seeking social support from commissioners, coaches, and peers; employing small coping mechanisms to overcome obstacles; and developing attitudes such as empathy, flexibility, and relativism. This study offers detailed insights into how students navigate uncertainty. Moving forward, efforts in uncertainty education should prioritize how educators can positively influence the development of metacognition in uncertainty.

KEYWORDS

uncertainty, transdisciplinary education, urban sustainability, metacognition, engineering education

1 Introduction

In the past two decades, the idea has grown that engineering education needs to change significantly to become sustainable (Leal Filho et al., 2018). Part of this transformation aims for education to engage with people from industry and other parts of society to work on sustainability challenges collaboratively (Knudsen, 2015). In transdisciplinary courses,

students are confronted with the uncertainties of real-life challenges and learn to collaborate with stakeholders in and outside of academia (Gallagher and Savage, 2020). Such educational reconfiguration also requires the investigation of new competencies for sustainability that are being taught there (Bianchi et al., 2022).

One of those new sustainability competencies presented in international frameworks by the European Commission (Bianchi et al., 2022) and UNESCO (2017), is the competency to deal with uncertainty. In simple terms, uncertainty refers both to things that are uncertain and people that feel uncertain (Uncertainty, n.d.). Sustainability challenges are often characterized as uncertain things, because of their dynamic and networked nature (Ingold et al., 2018). It is this kind of uncertainty that students and other people working in the sustainability domain need to deal with and that the previously mentioned frameworks refer to. A more detailed view of uncertainty in sustainability challenges suggests that uncertainty has several dimensions. The relational perspective of Brugnach et al. (2008) distinguishes between three dimensions of uncertainty: the unpredictability of a real-world challenge, the knowledge gaps in the problem, and the conflicting perspectives among the people involved. Previous research showed that students are likely to encounter all three dimensions of uncertainty in transdisciplinary courses (Bohm et al., 2024).

To be able to recognize the different dimensions of uncertainty, students need to be aware of the limits of their knowledge. Based on that awareness, students can think of approaches to regulate their thinking and learning about the uncertainty of sustainability challenges. Such awareness of one's knowledge and regulation of one's thinking is called 'metacognition' (Stanton et al., 2021). More than learning *about* sustainability, the transition in education should focus more on learning the new ways of thinking that sustainable transitions need to deal with their uncertainties (Zoller, 2015; Karjanto and Acelajado, 2022). However, what metacognitive awareness and regulation students need to deal with the different dimensions of uncertainty is unclear. Although the effectiveness of teaching metacognition is well-established in several meta-analysis studies (Perry et al., 2019), previous research also suggests that teachers find it difficult to formulate metacognitive learning objectives in transdisciplinary courses (Bohm et al., 2023b). Therefore, a better understanding of how students currently deal with uncertainty is necessary to make the teaching of this sustainability competency more explicit.

In this qualitative study, we investigate the question: What uncertainty do students encounter when working on sustainability challenges (metacognitive awareness) and how do they deal with it (metacognitive regulation)? We interview nine MSc students at three different moments of a 16-week, transdisciplinary course at a Dutch university of technology. The semi-structured interviews provide us with first insights into the development of metacognitive regulation of uncertainty throughout the course.

Section 2 presents the theory of metacognition and the sensitizing concepts that formed the starting point of the semi-structured interviews. In Section 3, we explain the course we used as a case study, the interview method, and how we used open coding to analyze the interviews. The results in Section 4 first show the awareness of uncertainty students talked about in the interviews, then the three groups of regulatory behavior we found they used to deal with them, and lastly, the connections between awareness and regulation. Finally, we discuss how uncertainty attitudes might be taught and further researched in sustainability education in the future.

2 Theoretical background

Metacognition is a well-established phenomenon in educational research. In this theoretical background, we first focus on foundational studies of metacognition that present a clear delineation of the field. We then zoom into uncertainty in more recent, explorative studies of metacognition, and how they point towards a further investigation of metacognition in the classroom.

2.1 Metacognition: awareness and regulation

Metacognition research commonly distinguishes two components of metacognition: metacognitive awareness and regulation (Veenman et al., 2006). In education, metacognitive knowledge generally refers to a student's (correct or incorrect) self-awareness or understanding of their knowledge or learning process. Metacognitive regulation allows a student to regulate their learning processes by, for instance, planning, monitoring, and evaluating them. Mevarech and Kramarski (2014, p. 36) describe that when metacognitive awareness and regulation are combined it enables students to self-regulate their learning:

> 'It [metacognition]enables learners to plan and allocate learning resources, monitor their current knowledge and skill levels, and evaluate their learning level at various points during problem-solving, knowledge acquisition or while achieving personal goals.'

Although metacognition is a cognitive process (*thinking*), metacognition can be aimed at affect as well (*thinking* about *feeling*) (Tobias and Everson, 1997). Thus, metacognition enables students to manage other aspects of learning beyond the cognitive, such as motivation and emotion (Ben-Eliyahu and Linnenbrink-Garcia, 2012). Equally, how well students can regulate negative and positive emotions while learning does influence their academic achievement (Zheng et al., 2023). Ben-Eliyahu (2021) suggests that specifically sustainable learning should allow for the development of metacognition in relation to emotion.

Overall, metacognition is strongly related to academic achievement, as several overview studies show (Dignath et al., 2008; Hattie, 2009; Perry et al., 2019). An understanding of what you know or how you learn is important to be able to progress in school. Metacognition is important for all school and age groups, from primary school to university (Perry et al., 2019).

Therefore, teaching metacognition is one of the most effective ways to improve learning in education (Quigley et al., 2016). Despite the evidence that underscores the importance of teaching metacognition, this study by Zohar and Barzilai (2013) showed that metacognitive instruction in practice is challenging to teachers. Additionally, teachers in transdisciplinary courses seldom write metacognitive learning objectives explicitly down in their course descriptions (Bohm et al., 2023b).

Veenman et al. (2006) suggest three criteria for effective metacognitive instruction. First, teaching metacognition should be an integrated part of the curriculum and not a separate and disconnected subject from the content. Second, it should be an explicit part of the curriculum and it should be clear to students why it is useful to them to learn (about) metacognition. Third, metacognition should be taught

over a longer period. The case study in this research matches these three criteria, which we will further elaborate on in Section 3.1, and it offers a favorable environment to further investigate uncertainty as a specific metacognitive competency.

2.2 Awareness and regulation of uncertainty in sustainability challenges

Complex, societal problems, such as the sustainability challenges this study looks at, create different kinds of uncertainty. In this study, we focus on the uncertainty that arises from the nature of complex problems (Koppenjan and Klijn, 2004). The complexity of sustainability challenges is that they are networked, unstructured, and dynamic (Leijten and de Bruijn, 2005). Therefore, problem-solving and decision-making about sustainability must be done in interaction with many stakeholders and with careful consideration of the uncertainties involved (Van Bueren et al., 2003).

Brugnach et al. (2008) defined three perspectives on uncertainty and Raadgever et al. (2011) used these perspectives to analyze uncertainty in sustainability challenges in environmental policy. First, *accepting not to know* relates to the unpredictability of a real-world challenge. Second, *knowing too little* describes the knowledge gaps in the problem. Third, *knowing too differently* arises from conflicting views amongst the people involved. These three perspectives on uncertainty will be used to analyze the awareness of uncertainty among the students in this study.

To analyze the regulation of uncertainty, no previous research has described what students do to regulate uncertainty in sustainability challenges. Generally, regulatory behavior by students can be, for instance, planning, monitoring, and evaluating their learning behavior (Stanton et al., 2021) or, more specifically, setting goals based on what motivates them and seeking help from peers (Zimmerman, 2023). However, specifically for uncertainty, what this regulatory behavior might be is unclear and only a few studies on uncertainty in education take metacognition into account. Smith (2002) investigates uncertainty in a stress management course, but the conclusions do not go into detail on student behavior. More recently, some studies on design education relate to uncertainty and metacognition (Cash et al., 2023). For instance, Christensen and Ball (2017) show that when designers encounter epistemic uncertainty it triggers what they call a 'metacognitive switch': a decision moment to continue with certain information or to immediately resolve uncertain aspects of the design. Furthermore, in the conclusion of their review study, the same authors suggest researching uncertainty in design education from the perspective of metacognition (Ball and Christensen, 2019). In general, Perry et al. (2019) point out that much educational metacognition research has been done in laboratory settings and that there is a need for more research in the classroom.

3 Materials and methods

3.1 Case study of a transdisciplinary course in urban sustainability

We researched student awareness of uncertainty and regulation of uncertainty in a transdisciplinary course on urban sustainability at a university of technology in the Netherlands. This course, comprising 24 ECTS[1] credits and forming an integral part of a two-year MSc program, provided students with real-life challenges in urban sustainability. Working in small groups of four or five, students tackled these challenges under the guidance of academic coaches (teachers from the university) and challenge commissioners (practitioners from the field). This integrative approach, coupling academic expertise with practical experiences from outside academia, ensured the course had a transdisciplinary character (Gallagher and Savage, 2020). In addition to providing a transdisciplinary learning environment, the course fostered transdisciplinary learning through teaching a 'living lab approach' that focuses on problem solving in the complex conditions of real-life challenges (Steen and Van Bueren, 2017).

The course incorporated metacognitive learning and teaching abiding by the three criteria for effective metacognitive instructions proposed by Veenman et al. (2006): (1) teaching metacognition integrated into the curriculum (and not as a separate course), (2) teaching it explicitly, and (3) teaching it over a longer period. Complying with the first criteria, the course taught metacognition integrated into the 'living lab approach', where students learned to build experiments and design solutions for urban sustainability challenges. Second, metacognition was part of three of the five learning objectives of the course. For example, learning objective three requires students to be able to examine and reflect on their learning experiences and set personal learning goals in the course. Such awareness of their own strengths and weaknesses, and regulation through goal setting can be recognized as metacognitive learning. For an overview of the course's learning objectives with an indication of those involving metacognition refer to Table 1. Lastly, the course ran for 16 weeks. Considering that most courses at this university take a maximum of 10 weeks, this is a longer period. We assume that during this period, the teachers (academic coaches) in the course would have had time to monitor and adjust students' metacognition.

3.2 Data collection through semi-structured interviews

We conducted in-depth, semi-structured interviews with nine students, each from a different team, at three moments in the course (27 interviews in total). The students were selected by an open call amongst all student teams in the course to participate in the research voluntarily. The participating students (four male and five female students) all had a bachelor's degree from either a university or a university of applied sciences. Those degrees were related to sustainability and innovation (four students), architecture and design (three students), or natural resource management (two students). Two students had previous work experience, but neither more than 7 years before starting this master's program.

1 ECTS is the abbreviation for 'European Credit Transfer and Accumulation System,' which is used across higher education institutes in the European Union as a common measure for learning based on specific learning outcomes and their associated workload (European Commission Directorate-General for Education Youth Sport Culture, 2015). Sixty ECTS credits are the equivalent of 1 full-time academic year of studies.

TABLE 1 The learning objectives in the case study course and which of them have metacognitive elements in them.

LO	Students who have completed this course will be able to:
1*	Iteratively improve and adjust the living lab process by continuous evaluation and incorporation of feedback;
2	Connect real-life challenges to academic theory and the living lab process;
3	Present in a way that enables exchange of knowledge, experience, and ideas with other staff, students, and stakeholders;
4*	Collaborate with societal actors involved in the challenge; and
5*	Examine and reflect upon personal motivations, values, and growth within the context of a learning experience.

Objectives marked with an asterisk (*) are considered related to metacognition, because they require awareness and regulation of learning, whether this is individual or in collaboration with others.

We interviewed the students after the plan development stage (after 4 weeks), in between the midterm and delivery of the final product (10 weeks), and when they finished the course (16 weeks). By interviewing at different moments, we gained insights into how students developed their awareness and regulation of uncertainty throughout the course.

The interview protocol was developed based on sensitizing concepts (Bowen, 2006) in the analytical framework that also formed the starting point for the coding process. We chose a qualitative research method because the competency of dealing with uncertainty has not been described in detail before. Therefore, the interviews aimed to provide us with first insights into the awareness and regulation of uncertainty that can be further developed and validated in future research (Brown et al., 2002).

In a previous study (Bohm et al., 2024), we assessed which dimensions of uncertainty were present in the sustainability challenges at the start of the course. Additionally, that earlier analysis categorized the dimensions of uncertainty on three levels [clear (1), complicated (2), and complex (3)]. Figure 1 shows the results of that assessment for the nine challenges that the interviewees in this study worked on. These were the uncertainties that students could recognize at the start. Additionally, the student interviews inform us which uncertainties might arise during the process that were not part of the initial challenge.

3.3 Analytical framework

To analyze uncertainty in a transdisciplinary course, we used the two-component model for metacognition (awareness and regulation), as it was first described by Brown (1987), but is still used in more recent metacognition research (Mevarech and Kramarski, 2014; Stanton et al., 2021). Based on that model, we integrated the three dimensions of uncertainty (Brugnach et al., 2008) to develop the analytical framework in Figure 2 that supported the data collection and analysis. The two components informed the interview questions with the students. First, we asked for the uncertainties that students recognized: the unpredictability of a real-world challenge, the knowledge gaps in the problem, and the conflicting perspectives amongst the people involved. Second, we asked how students deal with uncertainty to find how they regulated uncertainty once they became aware of it. Through an open coding approach, we looked for the regulatory behavior, such as mapping information or asking for help from peers (Zimmerman, 2023), that will enable them to deal with that uncertainty.

3.4 Data analysis through open coding

Two researchers coded the interviews in a consensus-based coding process. In the 27 interviews, 1,213 metacognitive quotations were coded, 589 codes in the 'awareness of uncertainty' category, and 624 in the 'regulation of uncertainty' category. To get to those results, the coding was done in three cycles.

The first coding cycle was aimed at establishing a codebook from the nine interviews at the end of the course. For the code category awareness of uncertainty, the first author used three *a priori* code groups: unpredictability, knowledge incompleteness, and knowledge frame multiplicity. Within those groups, open subcodes were assigned to the quotations. For the code category regulation of uncertainty, all codes were established through open coding.

For the second coding cycle, the second researcher used this first version of the codebook and added two codes in the awareness category and six codes in the regulation category. Especially in the latter category, the second coder added regulatory behavior that the first coder had merged under the same category. After the first two cycles, the code book contained 38 codes (16 codes for awareness of uncertainty and 21 codes for regulation of uncertainty).

In the third coding cycle, both researchers coded the next 18 interviews with this codebook. In this cycle, three codes were added to the awareness category, and six codes were added to the regulation category. The added codes described regulatory behavior that might not have been so important in the last part of the course, such as 'searching for information' or 'expectation management.' In this stage, we regrouped the codes into three emergent code categories: seeking social assistance, employing small strategies, and transforming attitudes. The final codebook contained 44 codes, 17 codes for awareness of uncertainty and 27 codes for regulation of uncertainty. Table 2 shows the codebook with short explanations of the codes.

4 Results

The results are presented in three parts: awareness of uncertainty (4.1), regulation of uncertainty (4.2), and connections between awareness and regulation (4.3). In the first two parts, we give a short overview of the results, before presenting the detailed results. In 4.3, we present the co-occurrence table of awareness and regulation.

4.1 Awareness of uncertainty

Students increasingly mentioned different kinds of uncertainty throughout the interviews (Figure 3). Figure 1 showed that all challenges contained uncertainty at the start of the course. Therefore,

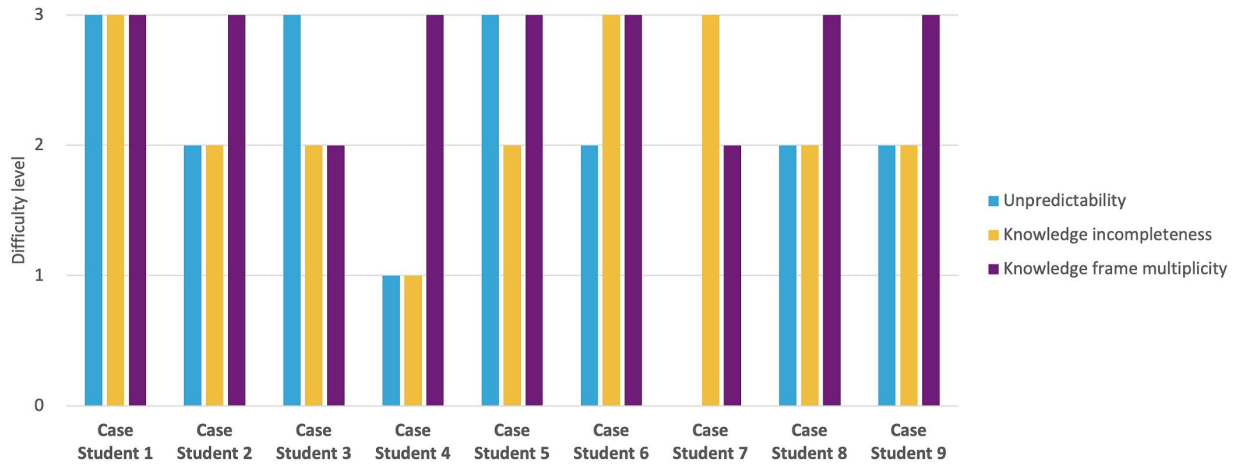

FIGURE 1
Assessment of the three uncertainty dimensions (unpredictability, knowledge incompleteness, and knowledge frame multiplicity) in the sustainability challenges of the nine interviewed students (Bohm et al., 2024).

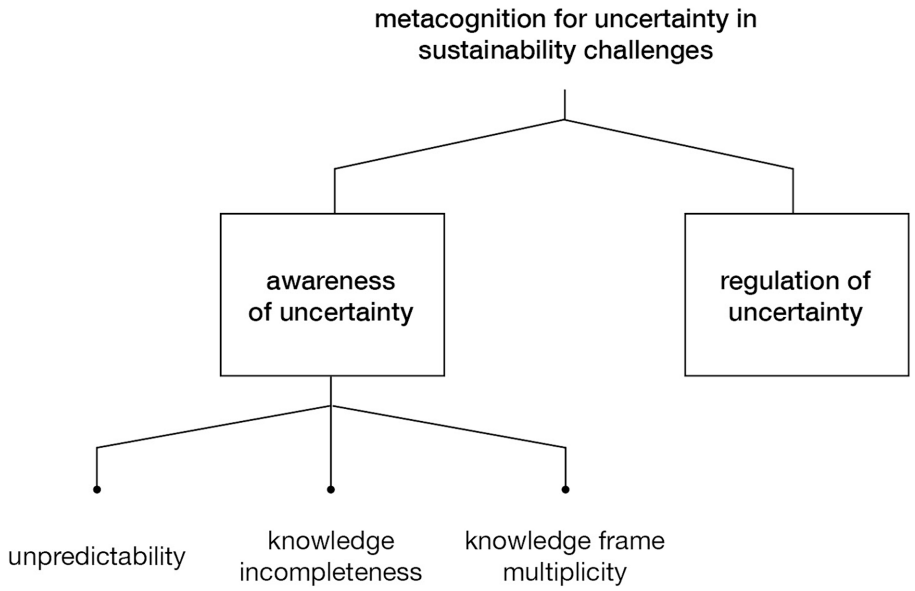

FIGURE 2
The analytical framework of this study is based on the two-component model of metacognition: awareness and regulation of uncertainty.

the results show that the interviewed students became more aware of uncertainty over time.

Specifically, unpredictability awareness grew throughout the course. In retrospect, it was easier for students to recognize which things emerged unexpectedly or surprised them. In the interviews, these things were mentioned as the unpredictable parts of the challenge.

Overall, students recognized uncertainties of the dimension 'multiple knowledge frames' most often. However, only three challenges contained this dimension as the most difficult level in Figure 1. Furthermore, even though knowledge incompleteness was the most difficult uncertainty dimension in most challenges according to Figure 1 (seven out of nine challenges), students mentioned this dimension least often.

4.1.1 Unpredictability

Students most often mentioned 'changes during the project' (in 21 interviews) and 'dynamic problem' (in 21 interviews). As new insights arose while working on the challenges, it caused students to rethink their previous steps. Student 1 said:

> 'If we had known beforehand that the commercial applicability of wood would not have been worthwhile to research, I think we would have focused much more on the reuse of material within the municipality. Because the entire financial motive [to research this] fell away.' [Student 1]

In this context, two students said they believed unpredictability was an inherent part of doing research. In the last interview round, six

TABLE 2 The final codebook presents the codes in two groups: awareness and regulation of uncertainty.

Metacognition	Code category	Code	Description
Awareness of uncertainty	Unpredictability	Changes during the project	Because of new insights arising during the project, the student would have made other decisions when looking back.
		Dynamic Problem	Uncertainty due to the different moving parts in the challenges (variability uncertainty).
		Time constraints	Uncertainty due to a lack of time to comprehend everything.
		Incomprehensible	Student describes the limitations of being able to know reality (ontological uncertainty).
		Achieving goals	Uncertainty if it would be possible to contact the people that the student wanted to reach out to.
		Pressure of grading	Uncertainty if the quality of the work would reach a certain grade.
	Knowledge incompleteness	Lack of knowledge	Student was unable to find certain answers or information.
		Unclarity assignment	Unclarity about the expectations of assignments.
		Unclarity roles	Searching for the position of the student or student team in collaboration with others.
		Unclear tasks	Not knowing what to do next.
		Data quality	Uncertainty about the quality of the data that the student gathered.
	Multiple knowledge frames	Different perspectives	Different perspectives on the problem, approach, or the solution direction that can be in conflict with each other. Students are depending on others to find answers to their questions.
		Conflict case owner	Challenges, tensions, or conflicts that arise from working with the case owner.
		Usefulness results	Uncertainty about the quality of the outcome and the usefulness for practice.
		Quality participation sessions	Uncertainty about the quality of the outcome of participation in the process.
		Expectations	Students are confronted with their own expectations of the course turning out different.
		Ambitions of team	Peer pressure arose through ambitions the team set out to achieve together.
Regulation of uncertainty	Seeking social assistance	Collaborative work	Making use of the expertise of other team members to solve a problem.
		Conversations case owner	Talking to the case owner about uncertainty (for instance in roles or differences in expectations).
		Conversations coach	Talking to the coach about uncertainty (for instance to clarify assignments).
		Conversations peers	Conversations with students outside of the team.
		Conversations team	Discussing challenges with other team members to resolve them or get a better understanding of them.
		Conversations with stakeholders	Talking to different stakeholders or experts.
		Examples from previous years	Looking at student work from previous years of the course.
	Changing attitudes	Adaptability	Accept, e.g., lack of knowledge, deal with it and look for another way to find a solution.
		Acceptance of conflict	Accept that conflict can be part of the process.
		Embracing uncertainty	Accept that certain knowledge is not available.
		Other attitudes	Student describes dealing with uncertainty as a specific attitude towards not knowing (embracing uncertainty). This can also be an emotional response to uncertainty.

(Continued)

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TABLE 2 (Continued)

Metacognition	Code category	Code	Description
		Cut the knot	Actively create moments in the team to make decisions.
		Experiment	Students accept that there is not enough information and just experiment with a solution: 'we will see.'
		Flexibility	Student describes a positive attitude towards change.
		Learning process	Framing the uncertainties or challenges as a valuable part of the learning process.
		Persistency	Stick to the plan and convincing others of this direction.
		Relativism	Letting go of responsibility or acknowledging that they cannot solve the problems.
		Articulate position	Student decides on position or focus.
		Trust in team members	Trust in the competency, expertise, or agreements with team members.
		Empathy	Empathy towards others that might have caused uncertainty.
	Employing small coping mechanisms	Ask for feedback	Ask for feedback from different people.
		Confrontation	Students confront stakeholders with different views or try to facilitate the conversation between stakeholders about those views.
		Expectation management	Managing expectations of case owner or other people in the project.
		Scenarios	Thinking of the challenges that could arise beforehand.
		Reporting the process	Describing the uncertainties in the report.
		Search for Information	Students search for more information or further research the challenge they ran into.
		Taking a break	Going home early or taking a walk.

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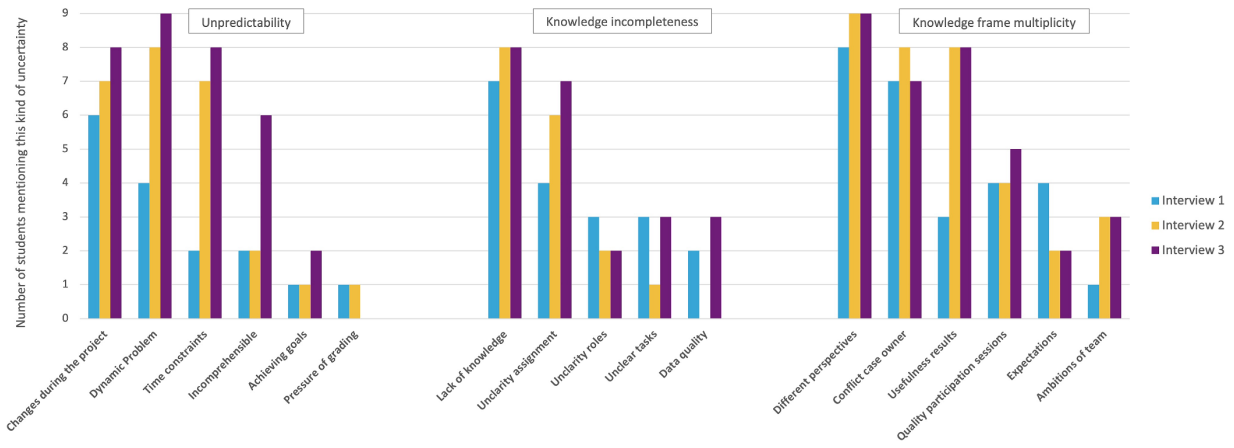

FIGURE 3
This bar chart shows which uncertainties students mentioned at different moments in the course, organized by the uncertainty dimensions: unpredictability, knowledge incompleteness, and knowledge frame multiplicity.

students mentioned uncertainty because the problem was incomprehensible to them. Often students saw the limitations of the research they did. For example, student 8 said:

> 'We held on to the outcomes of the interviews, where we found six barriers. But I think, that if you would go back into the literature now you can find many more, or that they will be described differently, or combined, or taken apart. There is an indefinite number of combinations possible.' [Student 8]

From the start, many students showed awareness of the problem being dynamic. In the final interview round, all students mentioned they encountered this uncertainty. We coded this uncertainty when students experienced constantly moving variables as part of the problem. This code often co-occurred with the code 'different perspectives' as part of knowledge frame multiplicity.

4.1.2 Knowledge incompleteness

In 23 interviews, students experienced a 'lack of knowledge'. Students mentioned this at the start, middle, and end of the course. This is an example from a student at the start of the course:

> 'Well, what I find difficult is that we are getting started with a challenge where we actually do not have much expertise on.' [Student 7]

Although the students gain expertise on the challenge during the course, the lack of knowledge does not decrease toward the end. Then, students found (unexpected) outcomes of their research uncovered new uncertainties to them:

> 'And, yes, there is now actually a chance that this system has already been in place for a long time, that this canal has existed for a long time, and that we have actually extracted wood from it. That could very well be the case. And that, I would have liked some more insights into that.' [Student 1]

Additionally, the unclarity of the assignment, roles, and tasks was another source of uncertainty. For example, when students mentioned that the assignment was unclear (17 interviews), they talked about different assignments in the course. Student 7 said to experience stress because of unclarity on the assignments in all stages of the project:

> 'At the start, we did not know what we had to do. In between, the uncertainty was about what we were going to make for the commissioner. In the end, we had difficulty deciding what to write down in the report.' [Student 6]

4.1.3 Knowledge frame multiplicity

In 26 of the 27 interviews, students encountered 'different perspectives'. In that case, the challenge presented different perspectives on the problem, approach, or solution direction that might contradict each other. Additionally, students also described different perspectives within their team. In this quote, student 7 explained how different groups had a different understanding of the problem:

> 'So someone who is committed to biodiversity in the city finds that much more important, for example, than someone who is committed to vulnerable groups and heat stress. So that was about the, yes, the weighing of those different, different consequences for those groups.' [Student 6]

A 'conflict with the commissioner' was mentioned in 22 interviews. In that case, specifically, differences in perspective with the commissioner caused uncertainty. Similarly, codes such as 'unclarity roles' and 'expectations' also refer to uncertainty in collaboration with a partner from outside of the university. Especially at the start of the course, students said they struggled with managing the expectations of the commissioner and giving direction to the research. However, in some cases, these conflicts were not completely resolved at the end of the course.

4.2 Regulation of uncertainty

The interviewed students described 27 kinds of behavior to regulate uncertainty. We grouped those into three categories: seeking

social assistance, employing small coping mechanisms, and changing attitudes to deal with uncertainty (Figure 4).

4.2.1 Seeking social assistance

The most prominent way to deal with uncertainty for the interviewed students was to talk about it, whether this was in conversations with other stakeholders (in 21 interviews), the commissioner (in 19 interviews), the coach (in 15 interviews), or their team members (in 20 interviews). Different uncertainties were resolved in those discussions. In conversations with the commissioner, students talked about the unclarity of roles in the process or managed expectations about the results. In conversations with the coach, students sought clarity on the assignments and advice on how to deal with their role and the role of the commissioner in the process. The conversations in the team were also about all these relational uncertainties and uncertainties arising from tasks. Student 4, for example, said:

> 'Especially from the moment we divided the tasks, if it was unclear to one of us how to proceed, we discussed together.' [Student 4]

4.2.2 Employing small coping mechanisms

Students mentioned several small coping mechanisms to deal with uncertainty and the feeling of being stuck, such as taking a break (6 interviews) or asking for feedback (3 interviews). One student said they made use of examples of the reports from last year in the course to deal with the unclarity of the assignment. Such behavior is often related to uncertainty in specific tasks.

4.2.3 Changing attitudes

Students talked about their attitude towards uncertainty in all interviews. In total, we found 13 different attitudes towards uncertainty, including an 'other attitudes' category. In 18 interviews, students said that they gained more understanding of the other perspectives of stakeholders in the challenge.

For some challenges, students started to look for consensus for the solution their project would develop, whereas other students developed an attitude of acceptance of the different perspectives. In 13 interviews students mentioned that they accepted conflict. Accordingly, some students specifically mentioned that failure or conflict were part of the learning process in the course. Student 3 said about accepting uncertainty:

> '[…] so part of dealing with it [the uncertainty] was also kind of letting go of the idea that you needed to know stuff before you could move on, or you could decide to just kind of accept it.' [Student 9]

10 interviews mentioned 'persistency' as an attitude towards uncertainty. Those students describe how they tried to persuade others of their story, solution, or interpretation of the problem. More often (in 13 interviews), students adapted their approaches. For example, Student 5 described how acceptance led to an adaptation of the project's approach:

> 'If you do not know the answer to something, you find a way to accept this and deal with it and find a different way to approach the problem.' [Student 5]

Some attitudes were related to knowledge or epistemology. One of those attitudes was 'relativism' (7 interviews) when a student doubts to what extent the world is knowable. For example, Student 1 said about relativism:

> 'I'm quick in thinking, I don't know things, then all of it is nonsense.' [Student 1]

4.3 Connecting awareness and regulation of uncertainty

The competence to deal with uncertainty is a combination of the awareness of uncertainty and using a strategy to deal with it. However, in the interviews, students did not always mention awareness and

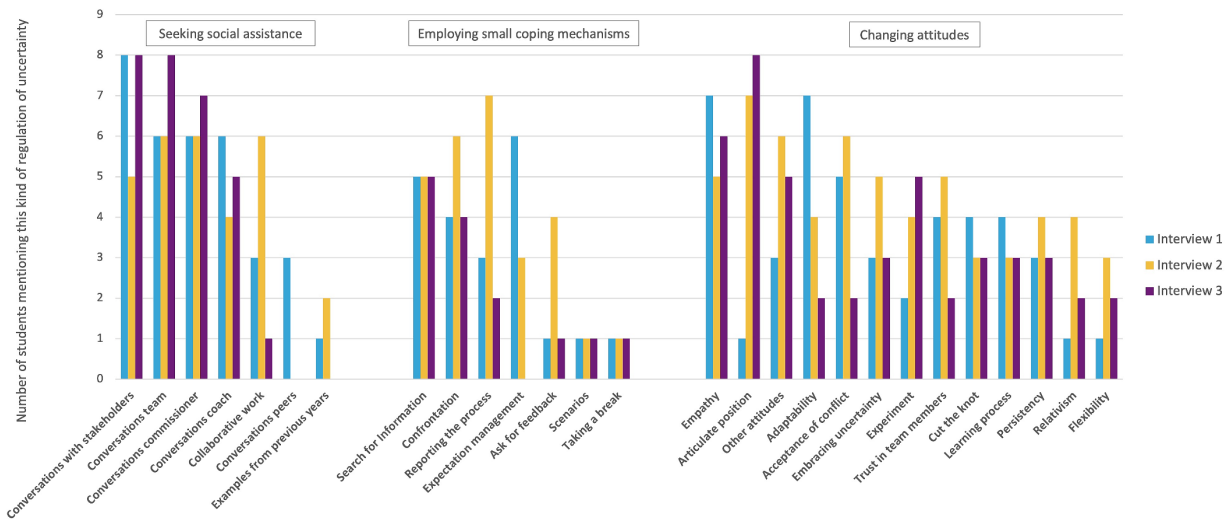

FIGURE 4
This bar chart shows which behavior students used to regulate uncertainty at different moments in the course, grouped into three categories: seeking social assistance, changing attitudes, and employing small coping mechanisms.

regulation in clear relation to each other. Sometimes, a student was able to clearly describe the unpredictability of the challenge, but could not directly answer the question 'How did you deal with that?' They might find an answer to that question later in the interview or were not able to connect the awareness and strategy at all. Therefore, the co-occurrence table that we present in Table 3 shows only the instances where a student did connect awareness and strategy to deal with uncertainty in the interview.

Students most frequently changed their attitudes to deal with uncertainty, independent of the dimension of uncertainty they encountered. Specifically, choosing their position towards the challenge and articulating that position was behavior across all three dimensions of uncertainty. Additionally, students went searching for new information (small coping mechanism) or talked to their commissioner, stakeholders, or their team members (social assistance) to regulate uncertainty in general. For knowledge incompleteness, students only use these generic behaviors, but for the other two uncertainty dimensions, we did find specific behavior that co-occurred in addition to the generic behaviors.

To deal with multiple knowledge frames, three kind of behavior related to attitude are mentioned more often: acceptance of conflict, persistence, and empathy. In the interviews, empathy seemed to be the starting point for understanding how different stakeholders perceive challenges. From that understanding, students chose either to accept the conflict or to persist in trying to convince the people involved to see it their way.

To deal with unpredictability, students adopted three attitudes in particular: learning process, flexibility, and relativism. Framing the course as a learning process allowed students to be mild about the unexpected events that made them rethink their choices or the mistakes they made. Students tended to either develop flexibility or relativism as an attitude towards unpredictability. Further research might investigate why students develop this tendency and if specific instruction might influence the development of those attitudes.

5 Discussion and conclusion

5.1 Discussion

The way students deal with uncertainty is highly individual and personal but, at the same time, develops depending on the kind of uncertainty they are confronted with and the assistance they receive. In this discussion, we first discuss the metacognition of uncertainty, how awareness of different kinds of uncertainty might lead to different regulatory behavior. Then, we take a closer look at the role of teachers in the development of uncertainty competency as an important practical implication of this study.

Throughout the course, students' awareness of the unpredictability of sustainability challenges grew. Brugnach et al. (2008) ascribe unpredictability to the complexity of the societal transitions that sometimes show non-linear and chaotic behavior. These authors advise responding by accepting these dynamics as they are and embracing the notion that their unpredictability will not change in the foreseeable future, is the way to deal with this kind of uncertainty. Attitudes accepting conflict and failure that the students in our study adopted correspond with this yet were not the only attitudes toward uncertainty they developed.

Regulating a lack of knowledge, because, for instance, data or people were not accessible, could lead to students responding with the flexibility to seek other approaches to achieve their goals. In some cases, when encountering knowledge frame multiplicity, students developed relativism and lost some of their confidence in what they were doing, or more drastically, their confidence in science.

Students are not the only ones to struggle with scientific expertise in the face of uncertainty. The realization that knowledge is contested and that several experts can give very contradicting advice is unsettling to many people (Koppenjan, 2007). In that context, de Bruijn and ten Heuvelhof (1999) suggest a process of constant interplay between research and decision-making. This process will lead to 'negotiated knowledge:' scientific knowledge that the involved actors can agree on. More recent scientific works investigate the development of reflexive practice, where students choose conscious moments to switch between the research of the problem and the design of a solution (Mierlo et al., 2010; Dorst, 2013; Popa et al., 2015). Overall, the uncertainty of sustainability challenges can not be addressed without also discussing the way that knowledge is constructed. In this, teachers might play an important role in addressing epistemic learning and integrating the different perspectives of students in the same team.

Our findings suggest that teachers can contribute to metacognitive learning on uncertainty in three ways. First, the collaboration with the coach in the course leads to less uncertainty than the collaboration with the commissioner. Students perceive the collaboration with the commissioner as a source of uncertainty related to knowledge frame multiplicity (Brugnach et al., 2008). The coach is only mentioned when seeking ways to deal with uncertainty but not as a source of uncertainty itself. Therefore, when seeking social assistance, students rather turn to the teacher than to the commissioner.

Second, 'seeking social assistance,' from peers, coaches, and commissioners, one of the original self-regulated learning strategies found by Zimmerman (1989), also is a prominent category in the results of this study. By asking for advice, feedback, or other kinds of help, students create their learning environment. The sense of agency that students need to be able to ask for help or feedback or otherwise regulate their learning, is one of the most important qualities in successful students (Zimmerman et al., 2017). Teachers play an important role to foster that sense of agency.

Third, several authors have found that teachers need to teach metacognition explicitly for it to be effective (Perry et al., 2019; Muteti et al., 2021). Additionally, the instruction of teachers becomes more effective when those teachers are aware of the learning strategies of students (Newell et al., 2004), and as this study shows, their attitudes toward uncertainty. Therefore, metacognition in sustainable education seems to be a key area for further investigation for teachers to guide the process of developing positive attitudes toward uncertainty.

5.2 Limitations and suggestions for future research

This study is limited by its explorative and qualitative character. The in-depth interviews that form the heart of the methodology are necessary to get to the difficult-to-measure concepts such as uncertainty and attitude. However, the conclusions presented here should be seen in the context of a single case study in a graduate

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TABLE 3 This table shows the co-occurrence of codes for the awareness of the three uncertainty dimensions with the codes for the regulation of uncertainty.

	Unpredictability	Knowledge incompleteness	Multiple knowledge frames
Seeking social assistance			
Collaborative work		3	1
Conversations coach	1	2	2
Conversations commissioner	3	5	12
Conversations peers			1
Conversations team	7	6	15
Conversations with stakeholders	4	3	8
Examples from previous years		1	
Employing small coping mechanisms			
Ask for feedback		2	4
Confrontation	4	1	6
Expectation management	3	1	4
Reporting the process			
Scenarios	5	7	4
Search for Information	1		
Taking a break		2	4
Changing attitudes			
Acceptance of conflict	3	1	10
Adaptability		1	1
Cut the knot	3	1	2
Embracing uncertainty	3	2	
Empathy	1	1	9
Experiment	3	2	2
Flexibility	5		
Learning process	4	1	1
Other attitudes	6	3	8
Persistency	1		5
Articulate position	9	7	14
Relativism	10	4	6
Trust in team members		1	1

(MSc) program, where students are relatively academically mature. This might have been visible in the diverse attitudes that students described. Where novices in epistemic learning might have more difficulty with reflecting on what is known and unknown to them, the students in this study had more practice experience in this kind of thinking and therefore, they could make their attitudes more easily explicit.

For a student to be able to seek social assistance is an important condition for self-regulated learning and it has been researched from the perspective of several educational theories (Zimmerman, 2023). However, the other two regulatory groups we found (small coping mechanisms and attitudes), are less well-established and require further investigation. That research is necessary to present the regulatory behavior we found with more clarity. Furthermore, research on how to teach metacognition for uncertainty could offer more support to teachers in their changing role as coaches in transdisciplinary courses. This way teachers will become better equipped to respond to students seeking social assistance from them when they try to deal with uncertainty.

5.3 Conclusion

This study provides the first insights into metacognitive awareness and regulation of uncertainty by students in transdisciplinary education. In 27 in-depth interviews, we asked 9 students at several moments in the course which uncertainties they experienced in the sustainability challenge they worked on and how they dealt with those uncertainties.

The results show that students most often encountered the multiplicity of the challenge when different people had different perspectives on the problem. Furthermore, throughout the course, students became increasingly aware of the unpredictability of the

challenge. Although, students conducted research and gained knowledge on the content of the challenge, knowledge incompleteness did not decrease throughout the course. Gaining new insights, also uncovered more uncertainties to the students.

Students used three kinds of regulatory behavior to deal with uncertainty. First, conversations with commissioners, coach, and their team members allow students to gain a better understanding of the uncertainty. Second, students use small coping mechanisms, such as taking a break or asking for feedback, to deal with uncertainties related to specific tasks. Third, students develop different attitudes toward not knowing, such as empathy, flexibility, and relativism.

Although more research is necessary to get a deeper understanding of metacognition in relation to uncertainty, this study underscores the importance of conversations between students, teachers, and peers as part of the learning process in transdisciplinary courses. Furthermore, dealing with uncertainty helps to grow self-awareness, and specific attitudes toward regulating knowledge. Ultimately, self-knowledge allows students to critically reflect on what they know, on what they do not know, and, most importantly, on what they can know. It is the task of this generation of students to anticipate what knowledge is needed to make strategic next steps toward a sustainable society.

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 TU Delft Human Research Ethics. 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

NB: Writing – original draft, Writing – review & editing. RK: Writing – review & editing, Writing – original draft. EB: Writing – review & editing, Writing – original draft. PB: Writing – review & editing, Writing – original draft.

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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.

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Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/feduc.2024.1362075/full#supplementary-material

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