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To cite this article: Elisabeth Jacoba Hendrika Spelt, Pieternelleke Arianne Luning, Martinus A. J. S. van Boekel & Martin Mulder (2017) A multidimensional approach to examine student interdisciplinary learning in science and engineering in higher education, European Journal of Engineering Education, 42:6, 761-774, DOI: [10.1080/03043797.2016.1224228](https://doi.org/10.1080/03043797.2016.1224228)

To link to this article: <https://doi.org/10.1080/03043797.2016.1224228>



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Published online: 17 Aug 2016.



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A multidimensional approach to examine student interdisciplinary learning in science and engineering in higher education

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ABSTRACT

Preparing science and engineering students to work in interdisciplinary teams necessitates research on teaching and learning of interdisciplinary thinking. A multidimensional approach was taken to examine student interdisciplinary learning in a master course on food quality management. The collected 615 student experiences were analysed for the cognitive, emotional, and social learning dimensions using the learning theory of Illeris. Of these 615 experiences, the analysis showed that students reported 214, 194, and 207 times on, respectively, the emotional, the cognitive, and the social dimension. Per learning dimension, key learning experiences featuring interdisciplinary learning were identified such as 'frustrations in selecting and matching disciplinary knowledge to complex problems' (*emotional*), 'understanding how to apply theoretical models or concepts to real-world situations' (*cognitive*), and 'socially engaging with peers to recognise similarities in perceptions and experiences' (*social*). Furthermore, the results showed that students appreciated the cognitive dimension relatively more than the emotional and social dimensions.

ARTICLE HISTORY

Received 31 March 2016
Accepted 8 August 2016

KEYWORDS

Interdisciplinary thinking; learning processes; student experiences; interdisciplinary course; higher education

1. Introduction

The importance of preparing science and engineering students to work in interdisciplinary teams is often emphasised in scientific literature (e.g. Auerbach 2015; Brown, Deletic, and Wong 2015; Foley 2016; MacKinnon, Hine, and Barnard 2013; Newswander and Borrego 2009; Richter and Paretto 2009; Vale et al. 2012). Science and engineering students will work during their careers in interdisciplinary teams on complex societal problems such as sustainability and food safety. In such teams, students need to be able to think interdisciplinary. This ability of interdisciplinary thinking is necessary to advance understanding when analysing and solving complex societal problems. Interdisciplinary team outcomes are results of the exchange of disciplinary knowledge and (inter-) disciplinary skills among team members. Research (e.g. Lyall and Meagher 2012; Pennington 2016; Sankowska and Söderlund 2015; Thompson 2009) showed that interdisciplinary team outcomes are more likely when each individual team member has prior experience of demonstrating interdisciplinary thinking and of working in such teams. For instance, being open minded, having tolerance to ambiguity and showing willingness to learn from each other's disciplines seem to be important team member characteristics for facilitating interdisciplinary collaborations, as found by Turner et al. (2015, 660).

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Additionally, Öberg (2009, 406) emphasised that newcomers often underestimate the challenges of interdisciplinary work and do not spend enough time to allow themselves to overcome disciplinary differences and to create common ground. Teaching interdisciplinary thinking to students in science and engineering in higher education starts early as possible to foster the skill development on working interdisciplinary (MacKinnon, Hine, and Barnard 2013; Tong 2010).

Previous research conceptualised interdisciplinary thinking as the demonstration of a complex cognitive skill (Van Merriënboer 1997) that constitutes of five sub-skills (Spelt et al. 2009). These five sub-skills are: (1) having knowledge of disciplines, (2) having knowledge of disciplinary paradigms, (3) having knowledge of interdisciplinarity, (4) higher order cognitive skills such as integrating the disciplinary knowledge, and (5) communication skills. The first three sub-skills relate to the acquisition of particular knowledge and the fourth and fifth sub-skills relate to the acquisition of particular skills. Hence, the complex cognitive skill of interdisciplinary thinking includes the combination of particular knowledge and abilities that students have to enact to demonstrate interdisciplinary thinking. For instance, students capable of interdisciplinary thinking demonstrate, on the one hand, disciplinary knowledge of relevant disciplines and, on the other hand, abilities to integrate disciplinary knowledge in a meaningful way. Teaching of interdisciplinary thinking by science and engineering teachers involves the teaching of these five sub-skills.

Disciplinary knowledge integration is the defining characteristic of interdisciplinary thinking (Klein 1990). As in multidisciplinary thinking, in interdisciplinary thinking, the relevant knowledge elements of each discipline are summarised. However, interdisciplinary thinking includes the extra step of connecting the identified disciplinary knowledge elements to bring about an advance in understanding. The ease with which disciplinary knowledge integration occurs, depends on the conceptual distance between the disciplines. For example, the integration of knowledge across sciences requires more cognitive effort compared to the integration of knowledge within a single science (Mingers and Brocklesby 1997). Feinstein and Kirchgasser (2015) advocated for science and engineering students who are engaged in complex problem solving, the integration of disciplines from natural and social sciences. The integrating of disciplines of different sciences is named in the literature as broad interdisciplinary thinking (Newell 2007). Broad interdisciplinary thinking is considered as being more challenging compared to narrow interdisciplinary thinking. This becomes visible in the pedagogical guidance to science and engineering students, in which teachers need to exemplify how the disciplines from natural and social sciences are to be integrated, so that students receive cognitive guidance on how to conduct broad interdisciplinary thinking (Spelt et al. 2015).

Examining student learning on interdisciplinary thinking contributes to the tailoring of this pedagogical guidance to science and engineering students. However, few publications can be found in the literature investigating interdisciplinary learning of students (e.g. Haynes and Brown Leonard 2010; Woods 2007). Accordingly, student learning in interdisciplinary master courses in science and engineering in higher education is yet not well understood. Therefore, the present study examines the course learning for an interdisciplinary master course on food quality management. This examination applied a multidimensional approach to analyse interdisciplinary learning. The multidimensional approach involves the approach of the cognitive, emotional, and social dimensions to learning, which are considered by Illeris (2002, 2007) as important learning dimensions and named, respectively, as: content, incentive, and interaction. Using these dimensions, the research questions were: (1) To what extent do science and engineering students report on the cognitive (content), emotional (incentive), and social (interaction) dimensions in learning interdisciplinary thinking? (2) Which key cognitive (content), emotional (incentive), and social (interaction) experiences feature interdisciplinary learning by science and engineering students? The aim of this investigation was to examine course interdisciplinary learning of students in order to advance scientific understanding on interdisciplinary teaching and learning in science and engineering in higher education by means of the aforementioned multidimensional approach. The multidimensional approach involves the cognitive, emotional, and social perspectives taken as analytical lens to examine students' learning journeys in interdisciplinary curricula and courses.

2. Previous research on interdisciplinary learning

Table 1 presents an overview of the major characteristics of previous research on interdisciplinary learning. As can be derived from Table 1, this previous research demonstrated a variety of approaches in examining interdisciplinary learning, which were majorly conducted in curricula in higher education. Additionally, this previous research on interdisciplinary learning, either theoretical or empirical, indicated that the cognitive, emotional, and social perspectives are present in student interdisciplinary learning which may refer to the cognitive, emotional, and social learning dimensions.

3. Learning dimensions of interdisciplinary learning

The learning dimensions being present in interdisciplinary learning (Table 1) are reflected in the acknowledged theory of Illeris (2002, 2007). Illeris describes learning as three interrelated dimensions: content, incentive, and interaction. The *content* dimension refers to the content to be learnt; it involves the *cognitive* part of the learning. The *incentive* dimension refers to the mobilisation of energy; it involves the *emotional* part of the learning. The dimension of *interaction* refers to the interactions with the environment; it involves the *social* part of the learning. The present investigation hypothesised that Illeris' learning theory (2002, 2007) can be used as multidimensional approach to analyse interdisciplinary learning of science and engineering students. Main argument for this hypothesis is that the learning of interdisciplinary thinking requires cognitive strategies (content dimension), emotional appraisals (incentive dimension), and social interactions (interaction dimension). More specifically, the cognitive strategies to be learnt are those for acquiring the relevant disciplinary knowledge and the interdisciplinary research skills. Additionally, the emotional appraisals to be dealt with are, for instance, those for valuing the usefulness of different disciplinary viewpoints. The social interactions to be learnt are the socially respectful interactions with multiple disciplinarians and interdisciplinarians.

Table 1. Overview of major characteristics of previous research examining interdisciplinary learning.

Focus	Type of study	Perspective	Theory	Context	Reference
Describes a theoretical model on stages of interdisciplinary learning	Theoretical	Cognitive	Structure of the Observed Learning Outcome (SOLO) taxonomy of Biggs and Collis	Interdisciplinary curricula	Ivanitskaya et al. (2002)
Presents a framework describing eight competencies for interdisciplinary communicative competence	Theoretical	Cognitive, emotional, and social	Byram's model of Intercultural Communicative Competence/Taxonomy of academic disciplines of Becher and Trowler	Interdisciplinary classroom communication	Woods (2007)
Describes interdisciplinary learning in terms of four cognitive processes using a pragmatic-constructionist view	Theoretical	Cognitive (emotional and social are suggested)	–	Interdisciplinary curricula and courses	Boix Mansilla (2010)
Describes three stages of intellectual development based upon the authors' student experience	Empirical	Cognitive, emotional, and social	–	Interdisciplinary curriculum	Graybill et al. (2006)
Categorises student experiences using a cognitive-constructive developmental lens	Empirical	Cognitive, emotional, and social	–	Interdisciplinary curriculum	Haynes and Brown Leonard (2010)
Examines student learning experiences using the lenses of doctoral student socialisation and identity development	Empirical	Cognitive, emotional, and social	–	Interdisciplinary curriculum	Holley (2015)

4. Research method

4.1. Course context

The interdisciplinary master course is part of an interdisciplinary master curriculum on food quality management. This two-year master curriculum provides disciplinary and interdisciplinary courses to science and engineering students. At least three interdisciplinary courses in food quality management are provided within this curriculum, being the 'core' interdisciplinary learning environment. The investigated course is the second course of these three interrelated interdisciplinary courses and is scheduled in the first year. The group of science and engineering students participating in this curriculum is heterogeneous; students from natural sciences and of social sciences participate in this interdisciplinary curriculum.

The curriculum on food quality management is provided at an European university of Life Sciences. This university delivers graduate and postgraduate education and research in the domain of healthy food and living environment. The university implemented years ago the outcome-based education approach to its education based upon the constructive alignment theory of Biggs and Tang (2007, 2011). Additionally, this university is dealing with the disciplinary knowledge integration between natural sciences and social sciences to address complex societal problems in its domain. This disciplinary knowledge integration is taught to graduate and postgraduate students and is also being demonstrated in the interdisciplinary research work done by this university.

Prior to the present examination of interdisciplinary learning, the interdisciplinary master course was redesigned (see Spelt et al. 2015). This was done to make sure that the selected course engaged students in interdisciplinary learning. The redesign considered the alignment of the teaching, learning, and assessing activities with the pre-determined interdisciplinary learning outcomes following Biggs and Tang (2007, 2011). The application of this pedagogical theory for designing curricula and courses with its distinctive constructive alignment principle is multiply recommended (e.g. Borrego and Cutler 2010; Gharaibeh et al. 2013) to the improvement of interdisciplinary teaching and learning. In line with the findings of Fiegel (2013), the use of this constructive alignment principle in the present study provided a clear course design to which a systematic investigation of interdisciplinary learning could take place by means of the learning dimensions of Illeris' learning theory. Additionally, as Holley (2009) found in her study, it is important for interdisciplinary education to have a joint understanding on the 'core' interdisciplinary learning environment and a well-designed overarching integrated framework should be the basis of this learning environment to develop students' ability on interdisciplinary thinking.

4.2. Course characteristics

The master course focuses on teaching broad interdisciplinary thinking in which students have to integrate disciplines from the natural sciences and social sciences. The course uses the 'techno-managerial approach', which has been advocated by Luning and Marcelis (2006) to be essential when analysing and solving food quality management problems. This approach includes both technological aspects from disciplines like for example food microbiology, and management aspects from disciplines such as logistics and psychology (Luning and Marcelis 2006, 2009). The embedding of an overarching framework showing the disciplines to integrate was covered by this approach (Holley 2009).

The techno-managerial approach (Luning and Marcelis 2009) considers four research phases to analyse and solve complex problems, which are: (1) the *appreciation* phase, in which the complex problem is appreciated from an interdisciplinary techno-managerial perspective; (2) the *analysis* phase to analyse the problem situation in more depth using the chosen techno-managerial disciplines; (3) the *assessment* phase to assess the problem situation in order to identify potential

causes of the complex problem; and (4) the *evaluation* phase to evaluate the solutions determined. The major course task is a complex problem on food quality management in a simulated food company. This problem-centring way of teaching in the present course was identified by Nikitina (2006) as one of the pedagogies for interdisciplinary learning.

The problem-solving task was an individual student task to make sure that each student was engaged in the disciplinary knowledge integration. Throughout the course, students also worked in groups, which were called 'learning communities' to share their experience on interdisciplinary research, to provide feedback on each other's research work and to become acquainted with working in interdisciplinary teams. Two teachers, one teacher of the natural sciences, and one of the social sciences provided pedagogical support to the students. This pedagogical support addressed the conduct of the problem-solving task and the achievement of the interdisciplinary learning outcomes. The problem-solving task consisted of eight assignments and each assignment instructed the students on the disciplinary knowledge integration referring to the particular research phase. This means that students conducting the full task were multiple times engaged in the conduct of interdisciplinary thinking which is highlighted by Spelt et al. (2009) as being important for disciplinary knowledge integration.

4.3. Data collection

The data collection instrument was a reflective learning journal, which was considered as appropriate for two reasons, namely, the gain of insights into student learning processes could be easily reached in this manner, and simultaneously, it could encourage students to adopt a critical attitude. The development of such a supportive reflective tool was based upon multiple recommendations (e.g. Boix Mansilla and Duraising 2007; Repko 2012; Woods 2007) to awaken students' awareness on, for instance, particular relevance of disciplinary knowledge in the performance of interdisciplinary thinking. This reflective journal was embedded in the individual problem-solving task; five of the eight assignments asked for a separate reflection activity on the experiences during interdisciplinary learning.

Students were two times plenary instructed on the writing of these reflective journals. They received instruction on the journaling activity itself and on its purpose to enhance interdisciplinary learning. The report of the journal was pre-structured into the report of two positive and two negative experiences to ensure that the capturing of interdisciplinary learning would be based on a full range of experiences, regardless of the value students assigned to their experience. Students were free to choose themselves on which learning experience they would like to report on and to assign it as either positive or negative. The data were digitally collected five times among 30 students; in total 615 experiences were collected and each reported learning experience counted for one unit of analysis. The course took 12 weeks and the data collection was spread almost equally over these weeks. The population of 30 students ranged in age from 23 to 41 years old, where 22 students were women and 8 were men, and 13 nationalities were represented. All 615 experiences collected were processed anonymously.

4.4. Data analysis

Two types of data analysis were performed: protocol coding and pattern coding. The protocol coding involved categorising the data using pre-determined codes (Miles, Huberman, and Saldaña 2013). All 615 experiences were coded by using the learning dimensions as a code. The code *content* referred to cognitive issues such as 'I learnt to integrate the different disciplinary knowledge'. The code *incentive* referred to emotional issues such as 'it was so difficult to integrate the different disciplinary knowledge'. The code *interaction* referred to interaction issues such as 'the feedback from my peer students improved the disciplinary knowledge connections made'. For current exploration to unravel students' learning journeys, the assignment of one code per unit of analysis was considered as sufficient for this

purpose. The protocol coding was done on each occasion of data collection ($t_1 - t_5$) using the qualitative data analysis software program MAXQDA 11 and resulted in frequency distributions. The protocol coding was carried out twice to validate the coding procedure. The percentage of agreement was 87% for t_1 , 85% for t_2 , 89% for t_3 , 88% for t_4 , and 82% for t_5 . The learning experiences that were coded differently were read again to reach agreement on the best fit between learning experience and code.

The second part of the data analysis used pattern coding to identify patterns across the reported experience. Pattern coding is a second-cycle coding method in which meaningful blocks of data are clustered together into a smaller number of themes (Saldaña 2009). The data on learning dimensions for each data collection occasion were clustered into data sub-sets on major themes. The identified themes were labelled, at a higher level of aggregation, namely as key experiences of interdisciplinary learning. Only those experiences that reflected a pattern were clustered and labelled.

5. Results and discussion

This section presents the first impression (Section 5.1) and the answers to the two research questions one (Section 5.2) by one (Section 5.3). Interpretations of these results were as much as possible being done with literature.

5.1. First impression of student learning in current study

The present examination of interdisciplinary learning showed variation in how a single experience was valued by students. The following example shows how two students valued the same learning experience of 'the identification of consequences for potential solutions to the given problem on food quality management'. The report designated as positive by the student was:

After some initial doubts, I was finally able to justify my strategy taking into account the managerial consequences of my strategy and the technological consequences of my managerial considerations. I could also find some more considerations that came up while regarding [with respect to] the strategy as a whole and not only with [for] the separate sub-solutions, so I consider that I had covered all the possible implications.

The report designated as negative by the student was: 'Finding technological consequences for [of] managerial solutions and vice versa was a challenge. For example, finding the technological consequences for [of] putting in place [a] training system based on [...] best practices'. A possible explanation of this difference in value accorded to the same kind of learning experience might be that the second student perceived the experience of integrating disciplines as frustrating rather than recognising it as the hard and fruitful work inherent to interdisciplinary thinking. According to Rives-East and Lima (2013), this value difference can also happen in interdisciplinary learning situations in which students start by negatively valuing learning situations as a result of their resistance and fear to learn new habits instead of positively valuing learning situations as a result of their efforts to step outside their disciplinary comfort zones. The effort made to step outside the disciplinary comfort zone consists of recognising connections between disciplines and being confronted with complex problems that have 'no right answer'. These efforts require a relatively high tolerance of ambiguity by engineering students as compared to learning situations in which students can 'stay' in their disciplines.

In addition, the examination of the interdisciplinary student learning processes showed learning activities that are necessary to achieve the pre-determined learning outcomes on broad interdisciplinary thinking. For example, one student reported: 'I still have difficulties in noticing whether the factors are managerial or technological ones. In my view, these two areas are often blurred, and the distinction are [is] unclear to me because they influence each other'. This learning experience illustrates student's attempt to identify mutual dependencies of technological and managerial factors. In addition, one student reported:

the research concerning the [food] quality behaviour where I have [to] figure out the importance of people [behaviour] have [has] an influence on the quality of the end product. More precisely, I have been fascinated by the different background people have (for instance, culture, attitude, motivation, and expectancy) and how they represent a dynamic factor to [be] take[n] into account besides the food dynamic [behaviour].

This learning experience illustrates the student's awareness of the influence of human characteristics (managerial perspective) in addition to food characteristics (technological perspective) on the quality of food products. Both report examples show students engaged in learning activities on broad interdisciplinary thinking. Similar to the findings of Haynes and Brown Leonard (2010), and Wright (2005), changes in how students formulated their experiences indicated that they were changing their thinking during the interdisciplinary learning processes. In this respect, the observed changes in thinking evolved from only technology oriented to also include managerial oriented, and vice versa. Moreover, it evolved from a disciplinary perspective to multidisciplinary perspectives and, eventually, to realising how to integrate knowledge of technological and managerial disciplines.

The examination of student interdisciplinary learning also showed research activities regarding the conduct of the interdisciplinary research phases (see Section 4.2). In the first phase, students appreciated the opportunity to apply knowledge of previous disciplinary courses to a real-world situation and to start searching for disciplinary knowledge within the technological and managerial disciplines in order to demarcate the complex problem. For instance, one student reported: 'A different way of thinking and looking at a problem. Thinking/looking at a problem situation from a managerial side and considering the managerial aspects as well – not only from the technological side'. Students also attempted in the first phase to clarify what was actually expected and they realised that their peers were facing similar struggles in conducting interdisciplinary research. In the second and third phases, students expressed the challenges they faced in connecting the technological and managerial factors into a conceptual model representing the complex problem. They also expressed their relief at their advance in understanding of the impact of decision-making in the previous research steps on the next steps. For example, one student expressed:

In the beginning of this assignment I had an idea of how to do the combination of the different sub-solutions to design the different [solution] strategies, but lately I realised that it was wrong and there was another way to do it, so that I could include both technological and managerial solutions.

In the fourth phase, students emphasised their advancement in understanding of how to conduct interdisciplinary research and how to figure out the best solution to the complex problem in a systematic way.

All in all, the examination of student interdisciplinary learning in the interdisciplinary master course features three aspects, namely, (a) the student assignment of either a positive or negative value to a similar learning experience; (b) the presence of learning activities to achieve the pre-determined learning outcomes on broad interdisciplinary thinking; and (c) the presence of research activities of the interdisciplinary research phases in food quality management.

5.2. Examining interdisciplinary learning with the dimensions (research question 1)

The examination with the three learning dimensions of interdisciplinary learning in the master course indicated the interplay of the content, incentive, and interaction dimensions. For instance, students reported on their differing levels of prior knowledge of technological and managerial disciplines (*content*) and on their frustrations at the disciplinary differences they encountered in how to identify factors influencing the complex problem under study (*incentive*), which prompted numerous discussions with peers and teachers to find ways to connect these disciplines (*interaction*). Another example of a potential interplay is the increase in knowledge on the role of disciplines in approaching complex problems (*content*), leading to an increased awareness of having a background in either technological or managerial disciplines (*incentive*), which in turn resulted in consultation of sources as literature, experts, and peers in order to counter the acknowledged lack of expertise (*interaction*).

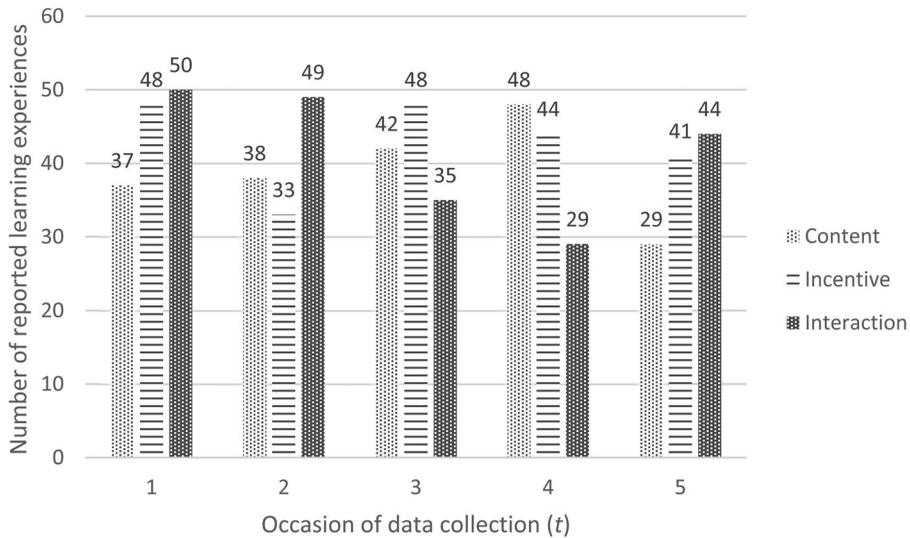


Figure 1. The frequency distribution of student report per dimension (content, incentive, and interaction) and occasion of data collection ($t_1 - t_5$).

The examination with the three learning dimensions of interdisciplinary learning showed that the dimensions were equally addressed by the students in their report. In particular, the examination of the 615 experiences showed that 194 experiences were related to the content dimension, 214 experiences were related to the incentive dimension, and 207 experiences were related to the interaction dimension. Considering the estimated analysis error rate of about 20% (see Section 4.4), the content, incentive, and interaction dimensions were thus equally addressed by the students during their learning. Figure 1 shows the frequency distribution of reported experiences by students per code and per occasion of data collection. There are no obvious differences in the variations between the reported experiences per learning dimension over time. Table 2 provides illustrations of reported experiences per learning dimension. The first illustration for the content dimension shows a gain in understanding, while the second illustration for the incentive dimension shows drivers for motivation, and the third illustration for the interaction dimension shows the social interaction between teacher and student.

Remarkably, the results showed that relatively more positive experiences were related to the content dimension (159 of 194) than to the incentive dimension (71 of 214) and to the interaction dimension (78 of 207). Figure 2 shows the number of experiences for each dimension categorised as positive and negative experiences. Apparently, students appreciated the cognitive part more than the emotional and social dimensions of the learning. A possible explanation for this might be the emotion transition observed by D' Mello and Graesser (2012) that confusion in learning can be transformed either into engagements/flows or into frustrations leading to boredom. In

Table 2. Illustrations of reported learning experience per learning dimension.

Learning dimension	Illustrations of reported learning experience
Content	'By searching for models, describing the essence and usefulness, I gained a deeper understanding of the linkage of T[echnological and M[anagerial] factors in models, they are not independent'
Incentive	'In these two first assignments knowledge from the past and experiences I had, emerged to the surface. The fact that you deal with a possible real problem in a company intrigues me and motivates [me] to deepen my knowledge in scientific areas that I wasn't familiar with'
Interaction	'Trying to overcome the language barrier that has become very evident between me and my teacher during teacher feedback session'

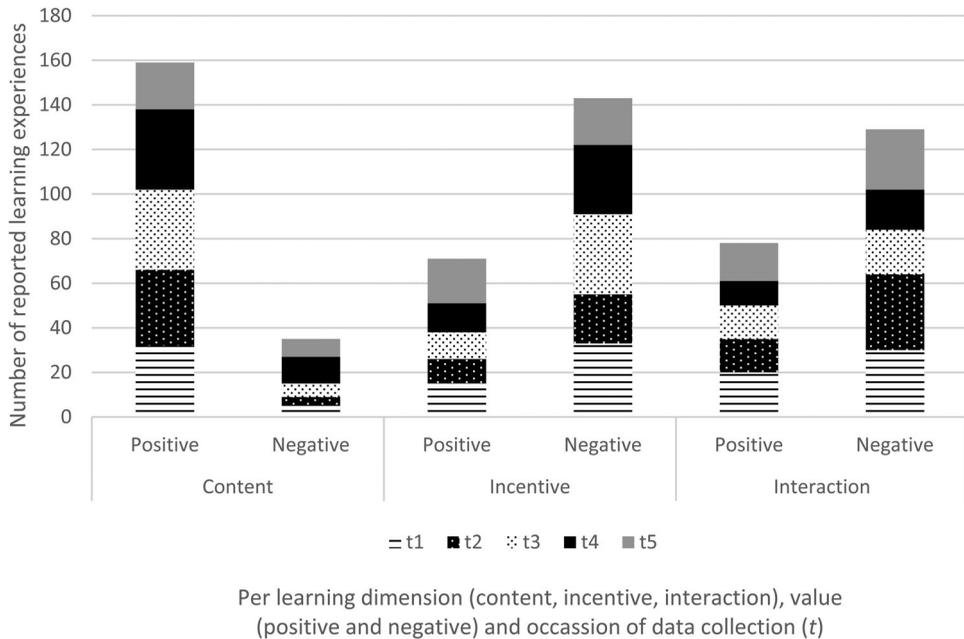


Figure 2. Number of learning experiences per dimension, value, and occasion of data collection ($t_1 - t_5$).

interdisciplinary learning, the necessary disciplinary boundary-crossing often gives rise to confusion. Since disciplines have different jargon, methods, epistemological viewpoints and so forth students get often confused once they start crossing disciplinary boundaries and start asking themselves 'what is a discipline?', 'what is seeking the truth in science?', and 'how do I perceive the disciplinary differences?' As Perry (1999) described in general and as Lattuca, Voigt, and Fath (2004) described for interdisciplinary higher education, these kinds of questions are evidence that students are growing intellectually, from the phase 'dualism' (i.e. students are able to make distinctions in 'right' or 'wrong'), via the phase 'relativism' (i.e. students are able to judge multiple perspectives) to the phase 'commitment' (i.e. students are able to commit to personal perspectives). However, this confusion is apparently perceived by students as negative and may lead to frustrations and finally to boredom. In contrast to this, from the teacher's point of view, confusion can be seen as valuable to student intellectual growth, especially when it develops into higher interdisciplinary engagements and ongoing learning flows. Hence, teaching strategies should focus not only on cognitive interventions, but also on incentive and social interventions in order that the student's confusion (D' Mello et al. 2014) may be steered in such a way that interdisciplinary learning is fostered. In turn, an increase in teaching focus on these interventions gives meaning to the confusion in students' minds and likely leads to better interdisciplinary learning processes.

In summary, the present examination using the three learning dimensions as analytical lens showed that interdisciplinary learning in the master course features (a) an interplay between these dimensions; (b) an equal distribution of student report on these dimensions; and (c) a relatively more appreciation of the content dimension compared to the incentive and interaction dimensions.

5.3. Key experiences per learning dimension (research question 2)

Table 3 presents key experiences per learning dimension of interdisciplinary learning and per interdisciplinary research phase (see Section 4.2). The key experiences found resemble those experiences that are seemingly essential for the conduct of interdisciplinary research in food quality management. The key experiences for the three dimensions indicate the presence of interrelationships between the

Table 3. Overview of key experiences per research phase and learning dimension.

Research phase	Key experiences per learning dimension
Content learning dimension	
1	Understanding how to apply theoretical models or concepts to real-world situations Becoming aware of disciplinary contributions to the analysis of complex problems
2	Developing searching skills for acquiring disciplinary knowledge Designing conceptual models representing disciplinary interrelationships
3	Realising the essence of all interdisciplinary research steps to be taken Recognising changes due to advanced insights into the interdisciplinary research
4	Recognising that answers can be based upon various uses of disciplinary knowledge Understanding the logic of interdisciplinary research and the pitfalls involved
Incentive learning dimension	
1	Frustrations in selecting and matching disciplinary knowledge to complex problems Feeling ambiguous about not having a clear view on how to frame complex problems
2	Irritation at the lack of the disciplinary knowledge to analyse complex problems Struggling to put different knowledge elements together in a meaningful way
3	Facing challenges in getting the exact information to diagnose complex problems Feeling relieved at what has been achieved compared to the intensive efforts
4	Mixed feelings about the integration of disciplinary solutions into one solution Feeling happy about the systematic manner and consistency in finding solutions
Interaction learning dimension	
1	Dealing with scheduled time for searching literature for various disciplines Socially engaging with peers to recognise similarities in perceptions and experiences
2	Dealing with lack of time in doing interdisciplinary research Socially engaging with teachers to receive feedback on being on the 'right' track or not
3	Dealing with the time needed to understand different viewpoints held by others Socially engaging with others to share the taken approach, arguments, and decisions
4	Interacting with literature to reach balanced disciplinary overviews Spending time on reviewing and finding arguments to construct a solid argument

three dimensions per research phase in food quality management. A potential interrelationship with respect to research phase 1 is, for instance, the gain in understanding of how to apply theoretical models and concepts to real-world situations (*content*) involves having frustrations in selecting and matching disciplinary knowledge to complex problems (*incentive*), and involves dealing with the scheduled time for searching literature for various disciplines on relevant theoretical models and concepts (*interaction*). Another potential interrelationship with respect to research phase 4 is, for instance, recognising that answers to complex problems can be based upon various combinations of disciplinary knowledge elements (*content*) involves having mixed feelings about the disciplinary knowledge integration (*incentive*), and requires the balancing between different disciplinary inputs (*interaction*).

Obviously, some key experiences reflect previously reported challenges in conducting interdisciplinary research (Clark and Wallace 2015; Golde and Alix Gallagher 1999; Lach 2014). For example, working across disciplines involves undertaking research in the absence of established frameworks, which results in the challenge to develop new analytical frameworks by putting disciplinary knowledge together. In addition, dealing with the time constraints is also considered as challenging in conducting interdisciplinary research (Sharp 2015).

To summarise, the key experiences found for interdisciplinary learning in this master course (a) resemble experiences of the interdisciplinary research process in food quality management; (b) indicate the presence of interrelationships between the learning dimensions; and (c) reflect the challenges encountered in conducting interdisciplinary research.

6. Conclusions and considerations

The applied multidimensional approach to examine student interdisciplinary learning in the interdisciplinary master course showed (see Figure 1) that the content (194 out of 615 experiences), incentive (214 out of 615 experiences), and interaction (207 out of 615 experiences) dimensions were equally

addressed by the students during their learning, and that the content is more highly appreciated (see [Figure 2](#)), relatively speaking, by the students than the incentive and interaction dimensions (*research question 1*). Noteworthy is that the less appreciative attitude towards the incentive and interaction dimensions should be acknowledged by science and engineering teachers as being an essential dimension of interdisciplinary learning in order to foster this kind of learning. The present research also concludes that the key learning experiences found (see [Table 3](#)) feature the common activities and challenges in conducting interdisciplinary research (*research question 2*). The hypothesised applicability of the learning dimensions (see [Section 3](#)) to examine interdisciplinary learning in science and engineering education, in addition to previous work in this field (see [Table 1](#)), seems to work out well (see [Tables 2](#) and [3](#)). More research is needed to validate this analytical lens and the accompanying method used.

Despite the journaling activity was considered as a suitable method for its purpose of examining interdisciplinary learning, the validity of experiences depends on the reflection capability of students. This may raise questions about the reflexivity being demonstrated in the writings of present research. Supplementary research methods, such as interviews and observations (e.g. [Gero 2016](#)), are therefore recommended to examine interdisciplinary learning. Additionally, although the learning dimensions of Illeris' theory provided a univocal coding frame, there were variations in coding (see [Section 4.4](#)) present. These variations are likely due to the existing dualism in coding ([Schreier 2012](#)). This dualism relates to whether coding is based on the manifest or literal meaning (meaning that is obvious at first sight) or the latent meaning (meaning that is not immediately obvious). The likelihood of this interference in the examination of student interdisciplinary learning needs attention in further research. Although the current analysis method seemed to be sufficient for its purpose of examining interdisciplinary learning, an elaboration of the developed method by assigning multiple codes to one unit of analysis is recognised.

7. Further research and implications

Replication studies are necessary in a wider context leading to multiple researchers examining course interdisciplinary learning in science and engineering in higher education with similar analytical lens and research method. Therefore, replication studies involving new cohorts of students participating in food quality management courses or in other interdisciplinary courses are recommended, thereby enabling the evaluation of the representativeness of the results gained. The present investigation can be extended by empirical research on relationships between the analysis of interdisciplinary learning processes and interdisciplinary learning outcomes as recommended by [Spelt et al. \(2009\)](#) using the recent developments on assessing interdisciplinary competence, reasoning, and communication ([Gvili et al. 2016](#); [Lattuca, Knight, and Bergom 2013](#); [Shen, Sung, and Zhang 2015](#)) and analysing interdisciplinary tasks ([Gouvea et al. 2013](#)). It would also be interesting to investigate whether students with a relatively more open and appreciative attitude towards other disciplines show other learning processes compared to students who have a relatively less open and appreciative attitude ([Gero 2016](#)).

For all these aforementioned further research directions, it is recommended that the educational settings implement the principles of the constructive alignment theory, as was implemented in the present study (see [Section 4.1](#)), to guarantee that students are really engaged in learning processes aiming to achieve interdisciplinary learning outcomes. Another implication for interdisciplinary education is that teachers should be better professionalised in teaching interdisciplinary thinking. To this end, teachers should become better acquainted with interdisciplinary thinking in their field, what interdisciplinary research differentiates from disciplinary research, and how constructively aligned educational designs need to be developed to foster interdisciplinary thinking among students.

All in all, successful interdisciplinary teaching and learning in higher education is resource intensive as recently highlighted by [Lyll et al. \(2015\)](#) and necessitates the teaching and learning on the content, incentive, and interaction dimensions as suggested by the present investigation.

Disclosure statement

No potential conflict of interest was reported by the authors.

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