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Exploring multidisciplinary teamwork of applied physics and engineering students in a challenge-based learning course

Canan Mesutoglu [a], Durdane Bayram-Jacobs [a], Johanna Vennix [a], Anne Limburg [b] and Birgit Pepin [b]

[a]Eindhoven School of Education, Eindhoven University of Technology, Eindhoven, Netherlands; [b]Applied Physics, Eindhoven University of Technology, Eindhoven, Netherlands

ABSTRACT

Background: In responding to the global problems facing humankind, there is great value in equipping science and engineering students with skills to function well in multidisciplinary teams. Little attention has been paid into the factors that influence multidisciplinary collaboration and teamwork of science and engineering students.
Purpose: This research describes multidisciplinary teamwork of applied physics and mechanical engineering students in a challenge-based learning (CBL) course. The study aimed to: a) identify the facilitators and barriers to multidisciplinary teamwork and b) explore learning outcomes connected to working in multidisciplinary teams.
Sample: 30 students registered to the course, two teachers, and three tutors participated in this research.
Design and Methods: An instrumental case study was conducted in the context of a pilot CBL course. Data included interviews, reflection reports, observations, and design posters. Transcribed video recordings were searched in an attempt to demonstrate the codes revealed with the qualitative content analysis of interview transcripts and reflection reports.
Results: The results indicated knowledge acquisition, application, and an awareness of other disciplinary approaches as the learning outcomes with some differences for engineering and physics students. The findings also yielded individual (e.g. knowledge of control theory), team (e.g. disciplinary perspectives), and course factors (e.g. disciplinary connections to the challenge) that influenced multidisciplinary teamwork.
Conclusion: Multidisciplinary teamwork is supported by the unique ways of thinking and approaching problems of the two disciplines. Implications contribute to future research and thinking for similar learning environments while improving student learning in multidisciplinary teams.

KEYWORDS
challenge-based learning; multidisciplinary teamwork; higher engineering education; STEM education

Introduction

Science and engineering professionals are expected to work collaboratively in order to respond to societal challenges and contribute to sustainable worldwide growth

CONTACT Durdane Bayram-Jacobs d.bayram.jacobs@tue.nl Eindhoven School of Education, Eindhoven University of Technology, PO Box: 513, 5600 MB, Eindhoven, Netherlands

(Accreditation Board for Engineering and Technology (ABET) 2021; Lassen and Nielsen 2011). In line with this, current practices in higher education put emphasis on students' use of different disciplinary backgrounds in teams. Students bring together the knowledge and methods of their disciplines as they work on complex, real-world problems (Schaffer et al. 2012). Recently, applications of challenge-based learning (CBL) have been increasing. Science, technology, engineering, and mathematics (STEM) departments are recognized as particularly compatible for CBL (Gallagher and Savage 2020; Leijon et al. 2021). CBL frames learning with: ' … challenges using multidisciplinary actors, technology-enhanced learning, multi-stakeholder collaboration, and an authentic, real-world focus' (Gallagher and Savage 2020, 1). Working on societal challenges in multidisciplinary teams is a core characteristic of CBL courses (Membrillo-Hernández et al. 2019).

Teamwork enables students to learn not only from interaction with the content but also from interaction with team members of other disciplines (van Breukelen, de Vries, and Schure 2017). Research puts forth that learning occurs in multidisciplinary teams of undergraduate science and engineering students through exchanging knowledge and perspectives across disciplines and reflecting this exchange in design solutions (Bakermans and Plotke 2018; Ludwig, Nagel, and Lewis 2017; Rådberg et al. 2020). However, little is known about the factors influencing student learning during multidisciplinary collaboration. As stated in the previous studies, students at times find it challenging to engage in the learning process during multidisciplinary teamwork (Sharma et al. 2017). Focusing on the influencing factors can improve the quality of multidisciplinary collaboration and thus promote student learning (Heikkinen and Isomöttönen 2015; Schaffer et al. 2012). Furthermore, it is often suggested that multidisciplinary teamwork leads to better student learning outcomes compared to monodisciplinary teamwork (e.g. Ludwig, Nagel, and Lewis 2017). Consequently, this study also examined how the students benefitted, if at all, from multidisciplinary teamwork along with the influencing factors. This background gave rise to two research questions: '1. what are the facilitators and barriers influencing collaboration and teamwork between applied physics and engineering students in a Systems and Control CBL course?' and '2. what are the student learning outcomes connected to working in the multidisciplinary teams?'

Theoretical framework

Multidisciplinary teamwork

This study adopted the definition for 'multidisciplinary education' by Ludwig, Nagel, and Lewis (2017) that frames STEM students' collaboration and learning in teams. The definition embraces educational experiences in multidisciplinary teams while acknowledging learning 'about, from, and with each other' (Ludwig, Nagel, and Lewis 2017, 2). Students' team learning behaviours include identification of their contribution to the problem, recognition of the contributions of the members of other disciplines, and a reflection of multiple disciplinary knowledge and methods in design solutions while managing conflicts (Borrego and Newswander 2008; Cutright, Evans, and Brantner 2014; Heikkinen and Isomöttönen 2015; Schaffer et al. 2012). Rådberg et al. (2020) pointed out that, in particular, the exchange of disciplinary knowledge and perspectives facilitates learning in multidisciplinary teams.

Although tasks are usually broken up according to disciplinary expertise in multidisciplinary teams, team members learn about the knowledge and methods of other disciplines (Borrego and Newswander 2008; Ludwig, Nagel, and Lewis 2017). Team composition in multidisciplinary engineering courses is frequently organized by having students of different engineering disciplines and by bringing together engineering and science students. Students share their disciplinary knowledge and skills that is not possible in a traditional setting (Debs et al. 2019).

Examination of perceptions and experiences of students who worked in teams of multiple engineering departments or in teams of science and engineering departments reveal that multidisciplinary collaboration leads to several learning outcomes e.g. improved abilities for problem formulation, higher level of disciplinary knowledge, recognition of team members' disciplinary contribution, improved learning motivation, and an appreciation of different disciplinary views in solving problems (e.g. Charosky et al. 2018; Heikkinen and Isomöttönen 2015; Keenahan and McCrum 2021; Knobloch et al. 2020; Kuo, Tseng, and Yang 2019; Ludwig, Nagel, and Lewis 2017; Rådberg et al. 2020; Sharma et al. 2017). Students view multidisciplinary teamwork as a positive influence on learning about the thinking processes and methods of other disciplines (Ali 2019; Cutright, Evans, and Brantner 2014; Knobloch et al. 2020; Seidel, Haemmerle, and Chambers 2007).

In this study, learning outcomes are understood as what the students: ' . . . end up with, intended or not, after some form of engagement' (Eisner 1979, 103). This research anticipated that results might show cognitive outcomes e.g. knowledge, cognitive strategies, and affective outcomes (Guo et al. 2020) when engaging in multidisciplinary teamwork in a CBL course. Behavioural outcomes (e.g. skills) were not measured in this research.

Although many studies report on better student learning outcomes associated with working in multidisciplinary teams, working together on design solutions and communication across disciplinary boundaries are often found to be difficult for students (Graff and Clark 2019; Sharma et al. 2017). A clear understanding of the factors related to multidisciplinary teamwork is likely to be useful.

Factors that influence multidisciplinary teamwork

Factors that influence multidisciplinary teamwork have more frequently been examined by health education studies (e.g. Almajed et al. 2016). Regarding undergraduate science and engineering students, the factors connected to learning experiences in multidisciplinary teams include the design problem, team composition, prior knowledge, positive team interaction, course materials, and personal characteristics (Aftab et al. 2015; Aloul et al. 2015; Debs et al. 2019; Keenahan and McCrum 2021; MacLeod and van der Veen 2020; Menekse, Purzer, and Heo 2019). Although these studies offer guidance for promoting better multidisciplinary teamwork experiences, only a few studies expressly undertook research to identify the factors influencing multidisciplinary teamwork (e.g. Aftab et al. 2015). According to Schaffer et al. (2012), for example, factors that influence learning in teams of students from multiple engineering fields are team composition, problem complexity, and prior experience in teams. From a different yet a complementary perspective, based on a summary of the literature, Cutright, Evans, and Brantner (2014) outlined elements required for the development of a multidisciplinary team of STEM students as: a) a faculty leader knowledgeable on the different disciplines, b) team-building activities, c) students' individual skills to work in the team, and d) a project with goals and deadlines that links the disciplines.

There are different course contexts where science and engineering students can collaborate in teams such as capstone design, project-based and other multidisciplinary courses. Multidisciplinary teamwork is a common practice in CBL courses. Students apply the knowledge and methods of their disciplines to communicate and to solve open-ended problems. Multidisciplinary teamwork in CBL and similar project-based courses have positive impacts on students' skills development and learning of course content (e.g. Heikkinen and Isomöttönen 2015). Since approaching a problem with the knowledge and methods of multiple disciplines lies at the core of CBL courses, CBL promotes student learning in multidisciplinary teams. Hence, in this study, we chose a CBL course to study multidisciplinarity and factors influencing teamwork.

Pedagogical framework

We used CBL as a pedagogy in responding to the research questions.

Challenge-based learning

There are concerns to sufficiently address societal problems, e.g. soil quality, sustainability as indicated, for example, by the National Academy of Engineering (2013, 3): ' … the problems are no longer contained in one continent … They transcend disciplines … ' To this end, CBL emerged as an approach that uses knowledge from multiple disciplines to develop solutions to a grand challenge.

Previous research has been concerned with innovative instruction for science and engineering students, which included interdisciplinary problems and teamwork (e.g. Siam and Abdo 2020). Rooted in pedagogical theories and methods such as problem-based learning, project-based learning, inquiry-based learning, and collaborative learning (Leijon et al. 2021; Membrillo-Hernández et al. 2019), CBL suggests unique features to facilitate learning e.g. involving local communities, collaborating with external experts and stakeholders, and reflecting on societal impacts and values (Gallagher and Savage 2020; Malmqvist, Rådberg, and Lundqvist 2015; Rådberg et al. 2020). Learners identify the problem to address in connection with the global theme or issue they are presented with and construct their own conclusions (Membrillo-Hernández et al. 2019).

The conceptual framework by Gallagher and Savage (2020, 18) on Figure 1 defines CBL with eight key characteristics while bringing clarity and standardization into CBL practices in higher education. Multidisciplinarity, one of the characteristics, refers to multidisciplinary collaboration and to challenges that borrow from multiple disciplines (Gallagher and Savage 2020). CBL is defined as a multidisciplinary pedagogy that fosters collaborative multidisciplinary experiences (van den Beemt, van de Watering, and Bots 2022).

Opportunities for science and engineering students to know each other contribute to their learning and preparation to professional life (Eames and Stewart 2008). Although multidisciplinary teamwork has shown to support student learning outcomes, one challenge is concerned with identifying the optimal conditions.

Figure 1. Conceptual framework for CBL characteristics.

Method

Research design

A case study approach was adopted to investigate the complex phenomenon of multidisciplinary teamwork in a pilot CBL course. Through an instrumental case study, data were analysed to gain a comprehensive picture of multidisciplinary teamwork in the CBL course (Creswell 2015).

Context of the study

This second-year bachelor course, 'CBL Systems and Control', highlights teamwork and collaboration as the main component of the learning process.

The teams worked on the challenge: 'design and implement a real-time controller for a pick-and-place robot'. The design constraints were: a) operating efficiently and b) meeting the requirements of a hypothetical customer. To be able to work in a reliable and energy-efficient way, the teams had to come up with a control and detection system that worked. The hardware in context is a robot arm set-up shown in Figure 2.

The course design is pedagogically situated on the framework for CBL characteristics (see Figure 1). A real-world challenge with global importance was defined. The teams were flexible in deciding upon the problem to solve which is related to the real-world. One team focused on waste management, where speed and distinguishing objects were important. Another team chose to focus on sorting fragile blood bags. Along with the robot arm set-up, technology is integrated into the course through online communication; Microsoft Teams channels separate for each team and the course learning management system; Canvas. A company developing pick-and-place robots for warehouses was involved as the stakeholder and provided feedback to the teams (e.g. Gallagher and Savage 2020). CBL is used as a flexible methodology; the pedagogical approach was further facilitated through: a) the engineering design process (Accreditation Board for Engineering and Technology (ABET) 2021) as the teams designed, implemented, evaluated, and optimized a controller and b) the elements to form

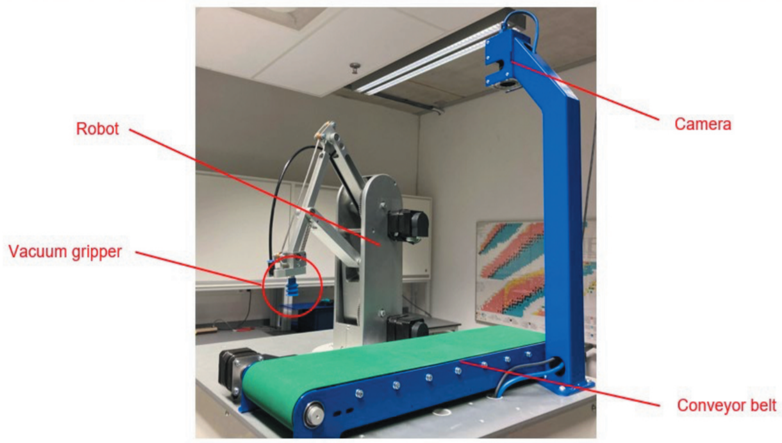

Figure 2. Robot arm in the lab.

multidisciplinary teams (Cutright, Evans, and Brantner 2014) e.g. a team of AP and ME teachers, a team-building activity, a challenge to connect AP and ME.

Three teams included one AP student and five ME students, whereas two teams included two AP students and four ME students. All team meetings were face-to-face. The meetings of one hour took place twice a week. Three tutors who were master students in ME, facilitated the team meetings. The course Canvas included resources such as the syllabus, details on the design challenge, presentations, videos, and external links. Appendix shows an overview of Canvas modules.

Participants of the study

Table 1 includes the participants of the study. Among the students who submitted a motivation letter, 30 were selected to which this study relates. Of the 30 students, there were three female and 27 male students. In total, seven AP students and 23 ME students were registered for the course. Most students reported experience in mono-disciplinary teams (52%), whereas a significant portion had none or little experience in multidisciplinary teams (54%).

Table 1. Data collection procedures.

Timing	Method	Participants and sampling	Construct(s)
At the end of the course	Student interviews	Four AP, eight ME students (n = 12). Purposive sampling: teams with two AP students and convenient sampling.	Facilitators and barriers, learning outcomes
	Teacher interviews	Two teachers and three tutors (n = 5). Convenient sampling: available participants.	Facilitators and barriers, learning outcomes
	Design products	Design posters of the five teams.	Learning outcomes
Final week of the course	Reflection reports	Individual reports (n = 30).	Facilitators and barriers
Four times during the course	Observations	Purposive sampling: a team with two AP students.	Facilitators and barriers

Data collection and procedures

This study used the first pilot of a CBL course with multidisciplinary teams of applied physics (AP) and mechanical engineering (ME) students. Table 1 presents the data collection procedures. Approval from the university ethics committee was obtained prior to data collection. All participants filled in informed consent forms.

Interviews

The Appendix presents exemplary interview questions. Participants were asked to comment on the key learning outcomes for the first section. Although the interview questions did not require reflecting on the learning outcomes separately for AP and ME students, often the participants expressed their opinions separately. The second section turns to factors that influenced multidisciplinary collaboration. The interview protocols went through minor revisions regarding length, context, and clarity following recommendations by two research experts. The interviews lasted around 30 minutes.

Design posters

Being the products of teamwork, the posters were used as a direct assessment of student learning in teams. All posters illustrated the problem identified, experiments performed, empirical results, and conclusion.

Reflection reports

Students reported on their course experiences related to: planning, collaboration, and presenting posters. The sections of the reflections for 'collaboration' that addressed multidisciplinarity were used as data.

Observations

Non-participant observations of team meetings were conducted on the second, fifth, seventh, and eighth weeks of the course. Each of the four video recordings was approximately 45 minutes in duration. The selected sections of the video recordings were transcribed and used to supplement the results of the interviews and the reflection reports (see Table 1). By using videotaped observations, it could be possible to examine what the students actually did and said while working together.

Data analysis

The audio-recorded interviews and the audible parts of the video recordings were transcribed verbatim and anonymized. A content analysis method (Miles and Huberman 1994) was followed for the qualitative analysis of the primary data, interview transcripts and the reflection reports. Using an inductive approach, common phrases and explanations could be located in the data. An initial screening was followed by the identification of emerging codes within the primary qualitative data (Yin 2016).

In the exploration of the factors to influence multidisciplinary teamwork, the conceptual framework by Salas et al. (2015) provided a structure in that the identified codes were matched to the three categories: individual factors, team factors, and course factors. These factors are reported to impact teamwork processes and products. Next, the frequencies and the percentages were calculated for each code. The percentages revealed the proportion of the instances a code appeared in the interview transcripts and the reflection reports (Miles and Huberman 1994). The observation excerpts were selectively used for capturing quotations representing the codes. Descriptions of the codes and direct quotations were used to display the data and to highlight the interpretation of the findings (Yin 2016).

Learning outcomes in higher education outlined by Guo et al. (2020) guided the analysis of interview transcripts for student learning outcomes. The total number of participants assigned with the emergent codes were calculated. For examination of the design posters, all teams receiving scores between 6.5–9 over 10 was interpreted as proof that all posters demonstrated a well-defined problem and an accomplished solution. In addition, according to the written feedback taken from one of the teachers, the posters had sufficiently indicated success in creating design solutions (MacLeod and van der Veen 2020). The posters were analysed for learning outcomes by two of the researchers. First, the researchers individually created a list of 'overall themes' addressed in the posters by examining the texts and the images (e.g. graphs, tables). The researchers agreed that an overall theme was: ' . . . the main idea observed in the posters, in other words, the foci' (Mena and Diefes-Dux 2012, 307). The researchers then discussed and reached a consensus on the final themes frequently addressed across the five posters (e.g. controller design, transfer function). The themes were then compared to the interview findings.

Trustworthiness

Iterative comparison of interview transcripts and reflection reports to the posters and the video recordings contributed to the trustworthiness of the findings (Yin 2016). An interrater reliability was calculated for the randomly selected pages of the interview transcripts and reflection reports. The selected pages constituted approximately 15% of the analysed transcripts. The coefficients ranged from .78 to .83 (Miles and Huberman 1994). Sharing findings with the teachers during a member check enhanced the accuracy of the study (Yin 2016).

Results

Figure 3 shows a summary of the results.

Facilitators and barriers that influence multidisciplinary teamwork

Table 2 presents the results for the factors that influenced multidisciplinary teamwork in the CBL course. The letters 'f' and 'b' demonstrate 'facilitators of' and 'barriers to' multidisciplinary teamwork respectively.

Individual factors

Results showed that 'lack of pre-knowledge of control theory' was seen as a barrier to multidisciplinary collaboration, especially during the early stages of the course. One ME student commented in the interview: 'AP students could catch up with the knowledge at the end of the project that led to more ideas . . . Similar level of knowledge would have saved time for teamwork'. An AP student explained in his reflection report: 'There was

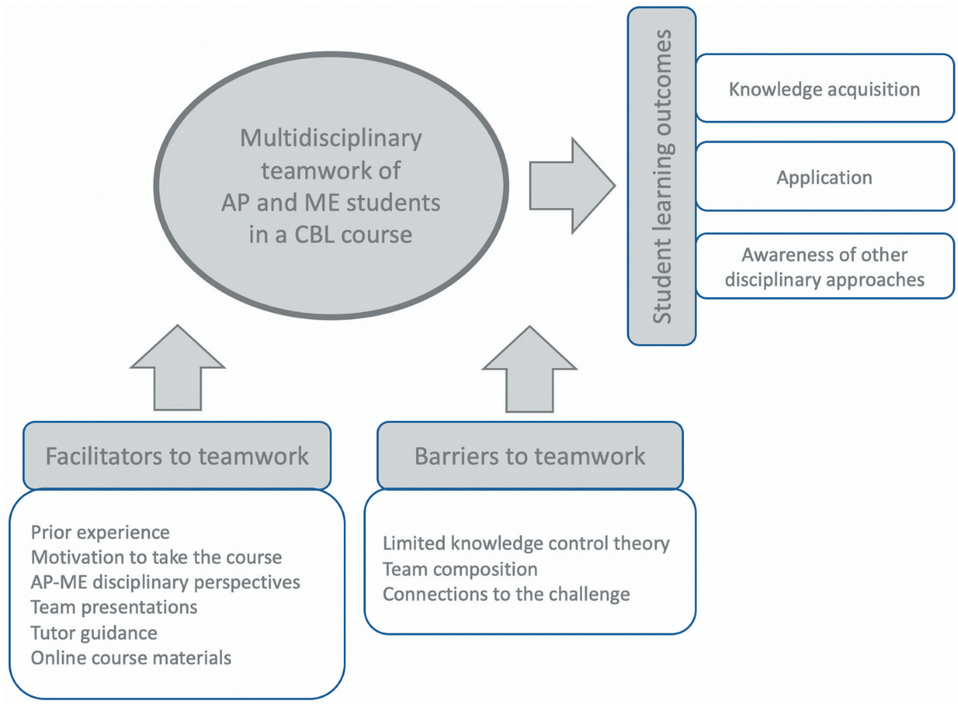

Figure 3. Summary of the study results.

Table 2. Factors to influence multidisciplinary teamwork in a CBL course.

Individual factors (31%)	Team factors (29%)	Course factors (40%)
Lack of pre-knowledge of control theory (b) (61%)	Communication (f) (41%)	Disciplinary connections of the design challenge (b) (54%)
Prior experience (f) (22%)	Disciplinary perspectives (f) (28%)	Tutor guidance (f) (26%)
Motivation (f) (16%)	Presentations (f) (16%)	Online course materials (f) (17%)
	Team composition (b) (15%)	

a huge gap . . . between the physics and the mechanical . . . it just makes it so that you're spending time on doing stuff while also having to spend time learning stuff'. Some ME students reflected on having to teach AP students about control theory: ' . . . they had to work harder than we did. That gap made it not as efficient between the translation of information . . . we couldn't spend hours trying to teach them . . . '

'Prior experience'; specifically, with teamwork, robotics, and coding was revealed as a facilitator. One AP student explained during the interview that not necessarily her AP knowledge but her work experience in robotics supported multidisciplinary teamwork: ' . . . we had to work with the robot itself. There I could help because I'm really practical. I have work experience with robots . . . ' 'Motivation' to take the course served as another facilitator. A tutor explained: 'They are willing to put in the effort . . . to understand the other side'.

Team factors

'Communication' emerged as a facilitator of multidisciplinary teamwork. Multiple instances in the video transcripts demonstrated how the students comfortably expressed their ideas, listened, asked questions, and provided suggestions.

A ME student appreciated 'disciplinary perspectives' in his interview: ' . . . we were stuck in the methods part . . . and they (AP students) brought a different view, more open minds to the project . . .'. Comment of a teacher to value the theoretical and the practical perspectives brought to the team was ' . . . So, one department is more practice oriented. And the other one's more theory. I think that was a really nice mix'. One of the AP students explained in his reflection report: ' . . . this was due to the theoretical knowledge of us and the handling of the engineering student. They knew how we should approach the problem despite their lack of theoretical knowledge compared to the AP student'. Table 3 shows a selected discourse for the exchange of theoretical and practical perspectives from the video recordings.

For 'presentations' during team meetings on empirical results and progress, a student comment during the interview was: 'Because you had to give a presentation to your teammates, you have to keep it at that level, bring stuff at that level. It was definitely a push to make it overseeable for everyone . . . ' Finally, the smaller number of AP students was perceived as a challenge suggesting 'team composition' as a barrier.

Course factors

Results indicated that 'disciplinary connections of the design challenge'; drawing mainly from the ME knowledge and methods was a barrier for teamwork. A student comment illustrated this point: ' . . . the physics part was way too little. If there was more physics, then the physics students could start to speak up more in the beginning and could contribute way more . . . ' 'Tutor guidance' is also reported to have facilitated multidisciplinary teamwork which included clarifications, asking questions, giving feedback, and supporting discussions where AP and ME students offered different insights. Table 4 illustrates an exemplary discourse.

The 'online course materials' on Canvas were perceived to be helpful in providing the necessary knowledge and in decreasing the knowledge gap on control theory. Table 5 shows an example discourse found in the video recordings.

Table 3. Discourse among team members-I.

AP-2	And how do we check this correct? How do we know that? With experiments?
ME-3	Yeah, with experiments to try different inputs . . . The transfer function should be the same or similar if you get the same result for different inputs. Other than that, I have no idea how to check.
AP-1	We (the AP students) tried to look at a central function . . . The thing we found with the imaginary impulse it's pretty stable. The transfer function feed forward might be correct. We got completely stuck and decided to ask you for help.
ME-2	I thought we should be able to measure the frequency response like a bode plot and find the transfer function that way.
AP-1	Do you think it would be possible to, theoretically, calculate the transfer function to calculate all the different differential equation?
ME-2	I don't think so because we don't know the coefficients. We don't know the spring constant.
AP-2	Maybe we could probably make some estimates.
ME-3	We just need to approximate stuff. But it's going to take time.

Table 4. Discourse among team members and tutor.

ME-1	If you are using the sin, you've already overcome the static part . . .
AP-1	But at the top it's still zero. What you see there, it stops and then starts moving and that is removed the network. So apparently something with the second?
Tutor	You notice that really nice. If you look at the graph on the left, you see that, that it goes to zero and then it does nothing and then sort of shoots and you can actually see that that part is static friction.
ME-1	Basically, overcoming minimum inputs, value is lower than some particular value.
Tutor	If you use a step function for the feedforward then you do not divide the coefficients. So, if the sin changes, if that part is static friction, then you look at the error and see OK now we will tune this parameter and see what happens if I make this bigger or smaller then if that part of the sin is correct then you know OK, my static friction is correct . . . So you actually not want to tune that together because it's very hard. One depends on another. So, what kind of function do you think you need to do to get the not static friction both like the normal friction?
AP-2	Constant velocity?

Table 5. Discourse among team members-II.

ME-2	At least one person can make sure they go and watch the frequency response video again and pick out exactly what it said that we should use because it. And then someone needs to try those input functions. But you guys saying that you want to do it before your experiment?
ME-3	Well, I think it would be very important to have the useful input before the experiment because if we just go and try the step function, I don't think that [not audible].
AP-1	I will use both the notes and the books and the lecture on Canvas.

Student learning outcomes

This section presents the analysis results of the interviews and the design posters.

Analysis of the interviews

Learning outcomes were grouped under three categories: a) knowledge acquisition, b) application, and c) awareness of other disciplinary approaches. 'Knowledge acquisition' was only attributed to AP students. More than half of the participants (n = 7) reported on AP students' knowledge acquisition on 'control theory' followed by 'general engineering knowledge' (n = 5). Illustrative comments by an AP student and a tutor for 'general engineering knowledge' were: 'I learned a lot from the field of ME. I can't say that they learned a lot from me. But I learned a lot from them . . . they were familiar with the subject, if I had questions, they explained it well . . . ' and 'It was mostly that the physics students had to know more ME content, not the other way around . . . '

The second category, 'application', involved comments on control measurements, inverse kinematics, transfer function, and using Simulink and Matlab for these measurements. Ten participants associated this category with AP students with frequent mention of inverse kinematics (n = 6), followed by using Matlab and Simulink (n= 3), and transfer function measurements (n = 2). 'Application' attributed to ME students by nine participants largely embraced using Matlab for application of control theory (n = 6), inverse kinematics (n = 2), and using Simulink (n = 1). These results underline that the application learning outcome mainly pointed to deepening engagement in inverse kinematics measurements for AP students, and in control measurements and Matlab for ME students. Two exemplary comments by an AP student and a teacher, respectively, were: 'The inverse kinematics was mostly what I did. And that was theoretical. I can do that fairly easily. I had a programme that I thought would help a lot, I worked a lot on . . . ' and ' . . . engineering students, they also learn a lot since they mainly had some theory about control ... this time they had to apply those theory to the system itself. So, it was different'.

The final category; 'awareness of other disciplinary approaches' captures remarks attributed to both ME students (n = 8) and to AP students (n = 6). The comments focused on the recognition of approaching and acting on problems through the lens of the other discipline. Results reveal that AP students realized the more practical orientation of ME students while the ME students noticed the theoretical orientation of AP students. For example, an AP student and a ME student commented: 'Our way of thinking was slightly different from ME students; we just do software theory. And they took the real-life system and looked at it and said, what one does actually do? Really nice thing to take away' and 'I gained insights of the AP part of how to attack a problem'.

The interviews showed that AP students benefitted more from multidisciplinary teamwork compared to ME students. Although the affective learning outcomes embrace all students, gains in knowledge were only revealed for AP students. Awareness of contributions by other disciplinary approach points to gains that cannot be possible in a monodisciplinary team. Considering the application learning outcome, the results suggest that the division of tasks resulted in students' deepening applications and practices within their comfort zone, mostly control measurements for ME students and inverse kinematics for AP students.

Examination of posters

The posters evidenced knowledge and applications related to 'control theory' to a great extent, followed by, 'transfer function, and 'kinematics equations'. Changes in 'feedforward and feedback controller design', 'frequency response function', 'cross-over frequencies', 'transfer function', 'test results of object detection in Matlab' were the highly referenced themes on the posters, followed by 'kinematics equations'. The teams also portrayed the results of measurements performed with Matlab to obtain the response of the robot and how Simulink was used to model the real-life system.

Reflections on the agreement between interviews and design posters

While the interviews suggested differences for AP and ME students, the results collectively indicated that by working in multidisciplinary teams, the students achieved gains in knowledge and applications of mainly control theory as well as transfer function and inverse kinematics through Simulink and Matlab models.

Discussion and implications

This section discusses the findings separately for the two research focuses, while the conclusion section compares and combines the findings.

Factors to influence multidisciplinary teamwork in a CBL course

Our results indicated that AP students' lack of prior knowledge of control theory was perceived as a barrier to multidisciplinary teamwork. This finding is interpreted in two ways. In the first case, common ground can be advocated for facilitating decision-making in multidisciplinary teams. Prausnitz and Bommarius (2011), for example, shared tutorials on biochemistry and diffusion basics to enable team members from departments other than biomolecular engineering have a common ground during teamwork. Similar to the findings of Knobloch et al. (2020), our finding on the course materials being a facilitator connects to the comments on AP students' catching up with the necessary baseline knowledge after some time in the course.

In the second case, the finding can be linked to another barrier in our findings; limited disciplinary connections to the design challenge. Due to the nature of the CBL course, the teams were free in formulating their problems. Although 'pick and place robot' was defined as a context to bring together ME and AP and thus help the teams develop as multidisciplinary (Cutright, Evans, and Brantner 2014), the main theme being control theory might have prevented the teams from identifying a problem that connected more strongly to AP concepts. According to Oliver, Ehrman, and Marasco (2019), for STEM students, autonomy on idea generation for a project is essential for the success of teamwork. Other findings stress the difficulty students have in communicating across disciplines to define and work on a problem in teams (Graff and Clark 2019; Rådberg et al. 2020). Providing more time to students to introduce their backgrounds and competencies might contribute to a problem definition with stronger disciplinary connections in a CBL course (Cutright, Evans, and Brantner 2014; Lassen and Nielsen 2011).

The significance of balanced disciplinary connections to the problem have frequently been addressed (Ali 2019; Aloul et al. 2015; Sharma et al. 2017). MacLeod and van der Veen (2020) highlighted how the students lose their sense of contribution to the project and feel less involved when the design problem fails to have a desirable level of connection to their discipline. Conclusions by Almajed et al. (2016, 1): ' . . . having a right mix of students and facilitating balanced participation . . . ' also address the importance of disciplinary connections to the problem as well as team composition. Furthermore, multidisciplinary team members do not need to have a shared background but to combine their expertise (Borrego and Newswander 2008; Keenahan and McCrum 2021; Rådberg et al. 2020). This interpretation once again suggests a team with a balanced composition of AP and ME students and a challenge that draws on knowledge of both disciplines.

Prior experience in teamwork and robotics was raised as a facilitator. This might relate to half of the students indicating to have had experience in mono- and multi-disciplinary teams before taking this CBL course. The finding can also be associated with the fact that students participated in team-building activities in the first two weeks of the course (Cutright, Evans, and Brantner 2014). Appreciation of existing skills as a facilitator is in line with Heikkinen and Isomöttönen (2015) in that, according to their results, working in multidisciplinary teams, students noticed how they can use their previous experiences, e.g., experience in creating websites, in a new context.

Our results confirmed that positive communication, previously identified as a factor that impacts all teams (e.g. Cohen and Bailey 1997), facilitates multidisciplinary collaboration (Debs et al. 2019; Menekse, Purzer, and Heo 2019; Sharma et al. 2017). The online channels are also found to contribute to this finding. Bringing unique perspectives to the team, more specifically, the theoretical perspective by AP students and a practical perspective by ME students, is identified as a facilitator. Other studies also found, for example, the importance of perspectives offered by different disciplines for effective multidisciplinary teamwork (Ali 2019; Keenahan and McCrum 2021; Knobloch et al. 2020; Ludwig, Nagel, and Lewis 2017). The practice- and theory-oriented perspectives and creativity brought to the teams by science and engineering students have previously been reported by other researchers (Bakermans and Plotke 2018; Kuo, Tseng, and Yang 2019). Scaffolding multidisciplinary science and engineering teams in supporting students' realization of their own disciplinary contribution and other disciplinary perspectives is often reported to foster learning (Menekse, Purzer, and Heo 2019; Schaffer et al. 2012). In line with this are tutor guidance and interim team presentations (e.g. Burgess et al. 2020; Debs et al. 2019; Prausnitz and Bommarius 2011). Gómez Puente, van Eijck, and Jochems (2013) showed that tutor questions during scaffolding of engineering students are more often process-related as opposed to content-related. Our findings extend this observation by showing the role of the tutors in highlighting the knowledge and methods of different disciplines during team discussions.

Student learning outcomes

Multidisciplinary teamwork promoted knowledge, application, and affective learning outcomes and our students performed well in responding to their identified problems. The findings highlight students' collaborative applications of software and tools in designing solutions in multidisciplinary teams (Ali 2019; Aloul et al. 2015). AP and ME students had similar experiences in engaging in measurements using the modeling tools. Our results contribute to research evidence showing that by working in multidisciplinary teams, students can update and deepen application outcomes in new contexts (Bakermans and Plotke 2018; Rådberg et al. 2020) in addition to developing knowledge of different disciplinary backgrounds (Ali 2019; Keenahan and McCrum 2021; Rådberg et al. 2020). Our findings are also in line with previous research demonstrating that multidisciplinary teamwork might lead to more learning outcomes for students of a particular discipline (Burgess et al. 2020). Our course seemingly has only supported AP students' knowledge acquisition. Gaining knowledge of a new disciplinary background supports the notion that learning in teams happens especially when students are out of their comfort zones (Charosky et al. 2018). To further extend on this, some students in the multidisciplinary teams of Heikkinen and Isomöttönen (2015) were first reluctant to work on tasks they were not familiar with. Results show that after taking on these tasks and working with new terminology and concepts, the students showed better learning outcomes. It might also be the case that, because all students were in their second year in their programs, they might have needed more time to achieve the knowledge required to represent their disciplines (Aloul et al. 2015; Cutright, Evans, and Brantner 2014).

Gaining an awareness of the perspective and thinking process of the other discipline confirms learning outcomes that cannot be attained in mono-disciplinary teams. Previous studies also showed science and engineering students' appreciation of each other's methods and perspectives through multidisciplinary teamwork (Ludwig, Nagel, and Lewis 2017; Seidel, Haemmerle, and Chambers 2007). Our findings should be understood in the context of some limitations. For example, we had a small and a particular sample; students with high motivation to take a CBL course.

Implications

At the practice level, the study provides an example for fostering multidisciplinary teamwork experiences in a CBL course. Findings show the importance of tutor guidance and interim team presentations in supporting multidisciplinary collaboration. Findings also reveal that participation by AP and ME students in the team lead to an awareness of disciplinary approaches and bring about the constructive difference in theory- and practice-oriented perspectives.

At the theoretical level, findings reflected mixed conclusions regarding the balance between openness of the challenge and degree of guidance (van den Beemt, van de Watering, and Bots 2022). Teachers are recommended to consider a range for explicitness on disciplinary connections of the challenge, for support with sources to bring students to an expected knowledge level, and for flexibility and guidance in problem formulation. Further studies considering course designs that fall within these ranges are recommended for a more in-depth understanding. Future studies can also include students who are not selected based on shown motivation and students of upper grade levels.

Conclusion

This research presents novelty through an exemplary CBL course and purposeful extraction of factors for successful multidisciplinary teamwork. Results indicate that multidisciplinary teamwork in a CBL course was beneficial for student learning despite some barriers to collaboration. There is also some evidence that AP students benefitted more with regard to knowledge acquisition.

Our finding on differences in learning outcomes for AP and ME students connects to perceiving team composition and the disciplinary connections of the design challenge as barriers to multidisciplinary collaboration. Although the design challenge allowed for an exchange of perspectives between AP and ME students, there is benefit in a stronger connection to AP concepts. A more even distribution of AP and ME students in the teams together with revising the challenge and guiding students' problem definitions such that AP knowledge input is also needed might facilitate students' being reliant on each other and thus generate more learning outcomes. Despite these barriers, it is vital that the results showed learning outcomes associated with awareness of different disciplinary ways of thinking. The results collectively suggest that the students first gained this recognition and later this gain was interpreted as a facilitator of multidisciplinary collaboration. Drawing on previous claims, (Keenahan and McCrum 2021; Ludwig, Nagel, and Lewis 2017) students' improved understanding of each other's profession during teamwork is an important contributor to learning. The findings for the learning outcomes taken together with the identified factors are interpreted as an indication that AP perspectives and approach to problems was useful for multidisciplinary teamwork and not necessarily AP knowledge.

Key conclusions are: a) multidisciplinary teamwork contributes to students' deepening their disciplinary practices while acquiring content knowledge of the other discipline, b) physics and engineering students' unique ways of thinking and approaching problems is a significant facilitator of teamwork, c) students in multidisciplinary teams can rely on both the perspectives and the knowledge of the represented disciplines, d) tutor guidance, interim team presentations, and online channels and materials are helpful for communication across disciplines, and e) the course can benefit from a balanced team composition and challenge with regard to AP knowledge, more time and coaching for problem identification. Future studies can verify the identified factors across a range of course contexts.

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ORCID

Canan Mesutoglu http://orcid.org/0000-0003-0520-0944
Durdane Bayram-Jacobs http://orcid.org/0000-0001-9502-1928
Johanna Vennix http://orcid.org/0000-0001-6295-7471
Birgit Pepin http://orcid.org/0000-0001-7804-145X

Consent statement

The authors declare that they have no competing interests. The authors have worked collaboratively at all stages of the research and manuscript preparation. All authors agreed with the content and gave consent to submit. Approval from the university ethics committee was obtained prior to data collection. All participants individually filled in informed consent forms.

Data availability statement

Raw data were generated at our institution and kept in a folder provided by the same institution. Data can be shared upon request from the corresponding author.

Ethical statement

The authors confirm that this research article has not been published elsewhere and is not under consideration by another journal.

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Appendix

Sample Interview Questions
Student interviews
Section 1

Please describe any learning outcomes that resulted from working with team members from another discipline?

How beneficial was multidisciplinary teamwork to your success and learning in this course?

Section 2

What are some of the factors that you perceive as facilitating learning in a multidisciplinary team?

Teacher interviews
Section 1

Please think back to the first weeks of this course when the students were introduced the challenge and how the team members interacted during that time. What are some of the things that you think students learnt as a result of working with members from another discipline?

Section 2

What are some factors that you perceive as impacting learning in a multidisciplinary student team?What do you think improved multidisciplinary collaboration?

Course Canvas