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Visualising the temporal aspects of collaborative inquiry-based learning processes in technology-enhanced physics learning

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ABSTRACT

This study presents new ways of visualising technology-enhanced collaborative inquiry-based learning (CIBL) processes in an undergraduate physics course. The data included screen-capture videos from a technology-enhanced learning environment and audio recordings of discussions between students. We performed a thematic analysis based on the phases of inquiry-based learning (IBL). The thematic analysis was complemented by a content analysis, in which we analysed whether the utilisation of technological tools was on a deep-level, surface-level, or non-existent basis. Student participation was measured in terms of frequency of contributions as well as in terms of impact. We visualised the sequence of the face-to-face interactions of two groups of five students by focussing on the temporal aspects of IBL, technology enhancement and collaborative learning. First, instead of the amount of time the groups spent on a specific IBL phase, the between-group differences in the most frequent transitions between the IBL phases determined their differential progress in the CIBL process. Second, we found that the transitions were triggered by the groups' ways of utilising technological tools either at the deep level or at the surface level. Finally, we found that the level of participation inequity remained stable throughout the CIBL process. As a result, only some of the members of the groups played a role in the most frequent transitions. Furthermore, this study reveals the need for scaffolds focussing on inquiry, technological and collaborative skills at the beginning of the learning process.

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Collaborative learning; inquiry-based learning; technology-enhanced learning; university physics learning; visualisation

Introduction

It is widely accepted that in order to support twenty-first-century science, technology, engineering, and mathematics (STEM) learning, new ways of enhancing higher education practices ought to be found. A growing number of studies have suggested that in STEM subjects, lecture-based instruction and teaching should be complemented by more active learning methods (Arthurs & Kreager, 2017; Freeman et al., 2014). In science education, inquiry-

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based learning (IBL) is a popular way to activate students (Pedaste et al., 2015). The advantages of IBL are well-documented in the context of higher education (Alfieri, Brooks, Aldrich, & Tenenbaum, 2011), and inquiry-based approaches can enable students to become familiar with scientific practices and to develop high-level reasoning skills (Bush, Sieber, Seiler, & Chandler, 2017). IBL is guided by one or more research questions provided by a teacher or proposed by students (Lazonder & Harmsen, 2016). To answer these questions, the students conduct experiments and collect data to reach justifiable conclusions. The IBL process can be divided into five phases: (1) orientate, (2) conceptualise, (3) investigate, (4) conclude and (5) discuss and review findings and conclusions as well as formulate suggestions for the next step. These five phases form the inquiry cycle, which engages students in an authentic scientific process (Pedaste et al., 2015).

As collaboration between students is beneficial for learning both science and the skills to do science (Jensen & Lawson, 2011), collaborative inquiry-based learning (CIBL) can help in addressing a wide range of challenges, such as low retention rates among students, (Freeman et al., 2014) facing STEM subjects today (Bell, Urhahne, Schanze, & Ploetzner, 2010). However, productive CIBL activities do not necessarily emerge without assistance (Kobbe et al., 2007). In arranging collaboration, different learning resources can be used to support learning (Jeong & Hmelo-Silver, 2010). External resources, such as technological solutions, can help improve learning outcomes (Çelik & Pektaş, 2017; De Wever, Hämäläinen, Voet, & Gielen, 2015) and support social interaction (Rau, Bowman, & Moore, 2017; Wagh, Cook-Whitt, & Wilensky, 2017). In technology-enhanced CIBL, students can utilise technology in every phase of their inquiry (Bell et al., 2010).

A recent meta-analysis of computer-supported collaborative learning in STEM indicated both positive and negative effects regarding productive collaborative learning (Hmelo-Silver, Jeong, Faulkner, & Hartley, 2017). Existing studies have mainly focussed on exploring collaborative learning situations with the help of atemporal coding schemes (Mercer, 2008) such as cumulative frequency counts and percentage values (Balgopal, Casper, Atadero, & Rambo-Hernandez, 2017; Leinonen, Asikainen, & Hirvonen, 2017; Sins, Savelsbergh, van Joolingen, & van Hout-Wolters, 2011; Summers & Volet, 2010). To develop a better understanding of collaborative processes, learning research requires the use of novel approaches and methods. There should be a focus on how to investigate and visualise the group processes that bring about group practices (Kapur, 2011; Mercer, 2008; Stahl, 2017). Up to now, visualisations have been utilised to observe productive interaction patterns and in further directing analyses (Thompson et al., 2013) in the context of science education (Williams & Clement, 2015).

This article builds on technology-enhanced CIBL as a pedagogical approach aimed at enhancing learning in the higher education context. We hypothesise that developing visualisations as a method to analyse temporal aspects of groups' CIBL processes reveals the need for scaffolds. The aim of these scaffolds should be to involve the members of groups in productive working processes in technology-enhanced learning (TEL) settings. First, we study the sequence of the transitions between the different phases of IBL, which have previously been studied using lag sequential analysis (e.g. Wang, Duh, Li, Lin, & Tsai, 2014). We elaborate these transitions by visualising how they emerge over time and identify the transitions that characterise technology-enhanced CIBL processes. Second, we examine how the groups utilise technological tools in these transitions (see also Jeong

& Hmelo-Silver, 2010). Specifically, we visualise whether the use of tools occurred at a deep level (e.g. structuring, analysing and interpreting information), surface level (e.g. routine manipulations and information collection) (de Jong & Ferguson-Hessler, 1996) or whether it was non-existent. Finally, our previous findings suggest that a high activity level is not always indicative of high-level collaboration (Hämäläinen & Arvaja, 2009). Therefore, we measure the participation of different students, not only in terms of frequency of contributions, but also in terms of impact in the different phases of the learning process. We address the following research questions (RQs): (1) What transitions characterise technology-enhanced CIBL processes at the group level? (2) How do the groups utilise technological tools in these transitions? (3) What do the visualisations reveal about individual students' participation in technology-enhanced CIBL processes?

Methods

Context of the study: primetime learning model

This study was conducted during a seven-week introductory physics course in thermodynamics and optics. The course was based on a new instructional strategy developed at a Finnish university – the primetime learning model (Koskinen, Lämsä, Maunuksela, Hämäläinen, & Viiri, 2018). The primetime learning process is comprised of four phases: principles, practice, problem solving, and primetime (presented in Table 1). There are no lectures or end-of-course exams. Instead, the assessment is formative, complemented by criteria-based self-, peer, and teacher assessments at the end of the course.

Our previous findings (Koskinen et al., 2018) indicate that the primetime learning model increased students' retention rate and maintained good learning outcomes in the courses in which the model was implemented. To better understand how students work

Table 1. Structure of the primetime learning model.

	Learning goal (Knowledge dimension[a])	Content	Implementation	Feedback
Principles	Forming an overall picture of the topic (Factual knowledge)	YouTube video clips in the TEL environment; course textbook	Self-studying twice a week before practice phase	Short multiple-choice test, from which student receives immediate feedback
Practice	Ensuring correct understanding and exercising technology-enhanced collaborative inquiry skills (Conceptual knowledge)	Conceptual problems in the TEL environment	Working face-to-face in the TEL environment twice weekly and without instructor	Feedback with correct answer immediately after solving a problem
Problem solving	Analysing realistic problems and applying the principles in realistic settings (Procedural knowledge)	Full-scale, context-rich physical problems	Independently or in small groups; submission of solutions to TEL environment before primetime	Correct solutions available after submission deadline; students review, rate and re-submit answers, which are verified by the instructor
Primetime	Evaluating own learning process and monitoring own learning goals with instructor (Meta-cognitive knowledge)	Challenges faced by the group during the previous phases	Instructor and a small group meet face-to-face during scheduled time	Feedback from instructor throughout course

[a](Krathwohl, 2002).

in small groups without an instructor in the TEL environment, as well as the kind of support they need, the present research focuses on the practice phase. In this phase, the groups solved conceptual problems face-to-face using a shared laptop computer, wherever and whenever necessary, as long as they completed two sets of problems before the end of each week. Before each session, the students self-studied key physical principles related to the group working session topic. Self-study consisted of several video clips and the relevant chapters of the course textbook (Knight, 2014). There was also a short test at the end of each self-study assignment. After the students completed both the self-study assignments and group working sessions, they were given full-scale physics problems to solve. At the end of each week, a primetime session was held between one group and the instructor, in which they discussed the challenges of the group.

Participants

The participants were second- and third-year university students in natural sciences ($N = 70$). Three course instructors (the first and third authors; the other authors were not involved in the teaching) divided the participants into 14 small groups (five students per group) based on a short questionnaire that the students had completed during the course registration. We estimated that five people would constitute a reasonable group size: The groups remained the same throughout the course, which meant that occasional non-attendance and possible drop-outs during the course could be tolerated. The number of groups could also be managed by our teaching resources. The students in a group shared similar schedules so that they could arrange common meetings. The groups were heterogeneous in terms of discipline and gender.

Data collection

We collected the data from the practice phase (Table 1) via screen captures and audio recordings of the group working sessions of four different groups ($n = 20$). The follow-up groups were the same throughout the course, and this article focuses on data of two groups. There were no instructors or researchers present for the group working sessions. The students received a license for the Screencast-O-Matic software (http://screencast-o-matic.com/home), which they used for screen capturing and audio recording. After each group working session, the groups sent their video and audio data to the first author via e-mail. The screen-capture videos showed the students' laptop use in the TEL environment, and the audio recordings captured discussions between the students. There were 56 screen-capture videos (14 per group, totalling 60 h). In addition to audio and video data, log data from the TEL environment were captured for all groups ($N = 14$) in order to ensure that the four groups selected for follow-up were close to average with regard to the amount of time spent using the TEL environment and the number of correct answers in the group working sessions.

Data analysis

First, we watched and listened to the video and audio recordings of the groups as they solved different types of problems, which we divided into four categories: (1) short conceptual multiple-choice questions, (2) short tasks demanding some calculations, (3) problems requiring the use of numerical methods and (4) problems including PhET simulations (Perkins et al., 2006). Among 21 problems, including technological tools to enhance CIBL, we used log data (time stamps and the relative amount of correct answers) to select a problem from the fifth group working session (week three of the course) for further analysis. First, when considering the open assignments on thermodynamics, the groups devoted, on average, the most time to this problem (approx. 19 min). Second, only about half of the groups (52%) succeeded in obtaining the correct solution to the problem, while, on average, 75% of the answers in thermodynamics were correct. The problem focussed on determining the time-dependence of the displacement of an atom in a gas (Figure 1(a)). The technological tools given to the students were a YouTube video clip (Figure 1(b)) and a script for numerical analysis (Figure 1(c)). We present an example of the output given by the script in Figure 1(d).

To answer RQ1, we performed a thematic analysis (Braun & Clarke, 2006). We identified units of analysis (or *themes*) that captured a meaningful unity from the students' conversations. We then recognised typical features of the IBL phases (Pedaste et al., 2015), as shown in Table 2, in which we present quotes of each phase (transcriptions translated from Finnish to English). As we labelled the units from the existing IBL framework, our method of analysis can be called theory-driven thematic analysis. Transitions

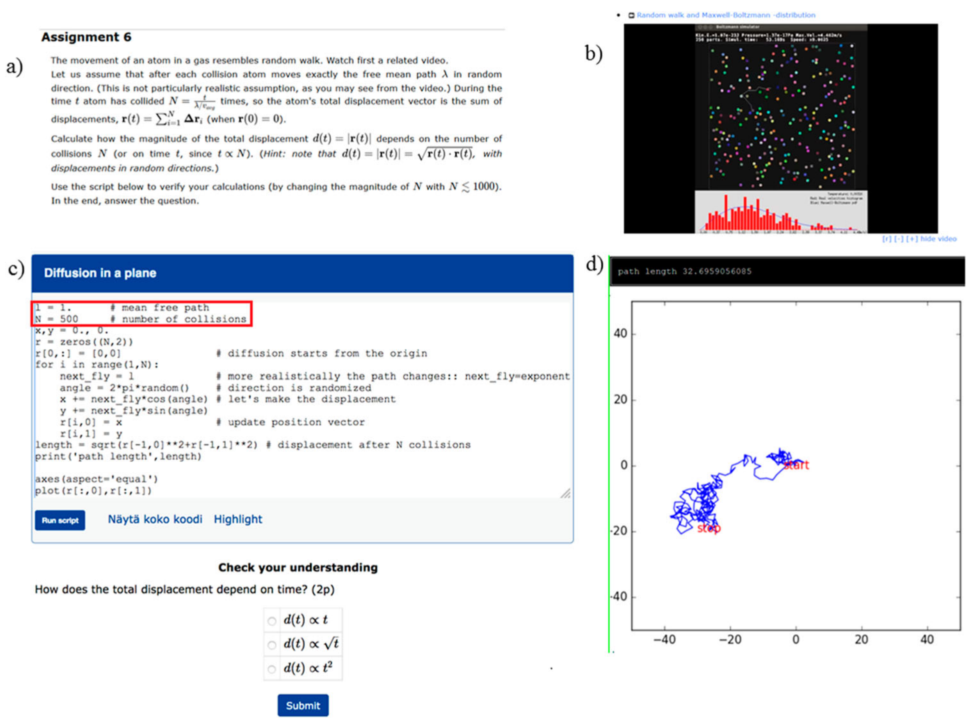

Figure 1. (a) Screen capture of the studied assignment; (b) Screen capture of the video clip; (c) Screen capture of the script. The parameters changed by the students are highlighted in red. (d) Example of the output (path length, i.e. the displacement of an atom and the graphical representation of its path) given by the script.

Table 2. Phases of inquiry-based learning with definitions and examples.

Phase	Definition	Example
Orientation	Stimulating interest and curiosity in relation to the problem. Identifying and clarifying the main concepts of the assignment. Getting familiar with the technological tools.	Viola: A position vector? That is, is that the position vector now if it moves that way here [drawing on paper at the same time]? Petri: Mmh? Viola: So, is the position vector this … ? Petri: Yes, it is. Viola: Or is it this, the whole … ? Petri: No, it is that straight line. Viola: It is this, is it? Petri: Yes, it is.
Conceptualisation	Determining concepts needed to solve the problem. Considering the frame of the study. Generating research questions or hypotheses.	Viola: So, we only have to [find out] how *N* [the number of collisions] is affecting it [the displacement], right? Krista: So, we have to get a formula that include *N* … Or some relationship. Petri: Mhm, what was the question? Or … The dependency on *t* [time]. Okay, the relationship between the displacement and time … How should we use time now?
Investigation	Planning, exploration or experimentation. Collecting, analysing and interpreting data.	Petri: So, these are varying … Viola: So, what you are doing is trying to determine the outcome using different values of *N* [Petri: Yes]. Then, it gives whatever. Petri: Yes, but it is a random [system]. Statistical … Viola: Okay, so approximately what is the order [of the displacement] … Petri: Yes, it was something like 20, approximately [$N = 300$ in the script]. Then it was a little bit more than 30. Let's now try when it [*N*] is 500. I'll try a couple of times: 11, 15, 25, 21, 15 …
Conclusion	Finding relationships and drawing conclusions from the inquiry. Offering or evaluating solutions to the research questions or hypotheses.	Juha: When thinking a little about this … When multiplying those with each other … Or when multiplying that with itself, i.e. the scalar product, we get all those scalar products with themselves, plus all those scalar products which go across. And that with itself, so … The length is … Proportional to *t* [time], so there is *t* squared inside and then there is that length, which is proportional to *t* to the power of four, so *d(t)* [displacement] would be proportional to *t*.
Discussion	Communicating and elaborating on the findings and conclusions. Making decisions. Reflecting on the process either at the end of IBL or in relation to a single phase of the cycle.	Petri: So, you would argue that it is proportional to *t*? Juha: Yes, I would do that – a wild guess. Petri: I will run this [the script] a couple of times. Viola: Where do those terms that go across disappear? Petri: Those terms do not disappear. It can be that they take it [the sum of the displacements] back to zero, or they can increase it. In principle, it would mean that if it randomly takes a direction, so … I mean away from the point, then it would clearly have to be [proportional to] *t*, but it can randomly turn back. Therefore, the best guess is *t*.

between the IBL phases separated the units from each other. We labelled the start and end times for each unit so as to visualise the CIBL processes over time by using MATLAB (https://www.mathworks.com/products/matlab.html). The visualisations allowed us to focus on the transitions between the IBL phases. In particular, we identified the transitions that characterised technology-enhanced CIBL processes at the group level.

To answer RQ2, we used data-based content analysis methods (Krippendorff, 2004) to study how the groups utilised the technological tools (the YouTube video clip and the script) in the different IBL phases. At the utterance level, we coded whether the utterance included references to the technological resources. First, the codes concretely described what the group was doing with the technology (e.g. watching the video, running the script or planning the use of the script). Altogether, we identified eight different codes. Second, we classified the codes as a surface- or deep-level use of technology, as shown in Table 3. The division was based on whether the technology utilisation was part of the integration of conceptual knowledge (deep-level use) or routine manipulations and information collection, which did not reveal active conceptual synthesising (surface-level use) (de Jong & Ferguson-Hessler, 1996). We visualised the CIBL processes over time (utterance by utterance) with respect to the utilisation of the technological tools in the different IBL phases. From the visualisations, we assessed how the groups utilised the technological tools in the transitions, which characterised the CIBL processes at the group level.

To answer RQ3, we visualised how the relative number of utterances made by different students evolved over time. In addition to the frequency of contributions, we coded the discussion at the utterance level by assigning an impact value of +1, 0 or −1 to each utterance (Kapur, Voiklis, & Kinzer, 2008), as shown in Table 4. The value depended on whether the utterance changed the direction of ongoing interaction and whether it moved the group towards (+1) or away from (−1) the goal of the inquiry. We then visualised how the cumulative impact value of each student developed over time. Finally, we studied how different students contributed to the transitions, which characterised the technology-enhanced CIBL processes. To get an overall picture of the learning processes of the groups, we synthesised the viewpoints of IBL, technology enhancement and collaborative learning with the visualisations.

The reliability of the coding was increased by the use of two coders. The first author coded 358 utterances, while another researcher outside of the study coded 218 utterances.

Table 3. Classes used when coding utterances were based on how the groups utilised the technological tools during inquiry.

Class	Description	Example
Surface-level use of technology	Technological tools are used for routine manipulations and information collection. This typically included watching the video, running the script and collecting or observing data given by the script.	Petri: Yeah, there it [the displacement] was about 20 [the number of collisions $N = 300$]. When N was 700, it was slightly over 30. Let's try with $N = 500$. I'll run this [the script] a couple of times: 11, 15, 25, 21, 15 … [The values of the displacement]
Deep-level use of technology	The technological tools are used for structuring, analysing and interpreting information. This typically included asking a question about the video, interpreting the script itself, modifying the script, interpreting or explaining the results given by the script and planning the use of the script.	Lasse: I was just about to say that it looks quite linear. But we can determine whether it is like square root [displacement proportional to the square root of t] or linear, if you set $N = 2000$ [in the script], for instance.

Table 4. Impact values given to each utterance and description (with examples).

Impact value	Description	Example
+1	An utterance moves a group towards the goal of the inquiry by planning and structuring IBL or making and offering suggestions that include fair ideas of how the group could investigate the topic under study.	Lasse: So, the question is that we have to determine how it … if the number of collisions increases or decreases; so how does it affect the distance, which it [the atom] travels … The atom …
0	An utterance does not move a group towards or away from its goal when it involves a question that does not include any presuppositions or if it echoes the others' ideas.	Iida: Mm.
−1	An utterance moves a group away from its goal when it includes misconceptions (as in the example) or suggestions that mislead the group during their learning activities.	Lasse: … There … So does it [*d(t)* in the assignment] mean that … Hmm … It means differential displacement [i.e. 'infinitely short' displacement] during time interval *t*, doesn't it?

Another researcher who was familiar with the IBL framework was able to code the transcribed text with the help of a coding manual, in which the coding procedure was explained in detail. After forming the units of analysis and independently coding the units and utterances, disagreements were discussed and completely resolved collaboratively by consulting the video and audio recordings.

Results

In what follows, we focus on the technology-enhanced CIBL processes of two different groups in their face-to-face study of the time-dependence of the displacement of an atom in a gas (Figure 1). The groups were selected to illustrate differences in the CIBL processes regarding the problem; only Group 2 succeeded in solving it correctly. First, by means of visualisations, we identify the transitions between the IBL phases characterising the technology-enhanced CIBL processes of the groups. Second, we illustrate how the groups utilise the technological tools in these transitions. Finally, we present what visualisations reveal about individual students' participation in the technology-enhanced CIBL processes.

The most frequent transitions characterise CIBL processes

Instead of the amount of time groups spent in certain IBL phases (Table 5), the most frequent transitions between the phases (in Figure 2, these are marked with arrows in the

Table 5. The amount of time the groups spent and the number of utterances they made in the different IBL phases.

	Group 1				Group 2			
Phase	Time (min)	%	Utterances	%	Time (min)	%	Utterances	%
Orientation	6.2	46	68	49	4.8	27	46	21
Conceptualisation	1.9	14	31	22	1.3	7	25	11
Investigation	2.0	15	10	7	4.8	27	76	35
Conclusion	0.6	4	2	1	0.8	4	8	4
Discussion	2.8	21	29	21	6.1	34	63	29
Total	13.5	100	140	100	17.8	100	218	100
Silence	4.3				4.0			
Sum	17.8				21.8			

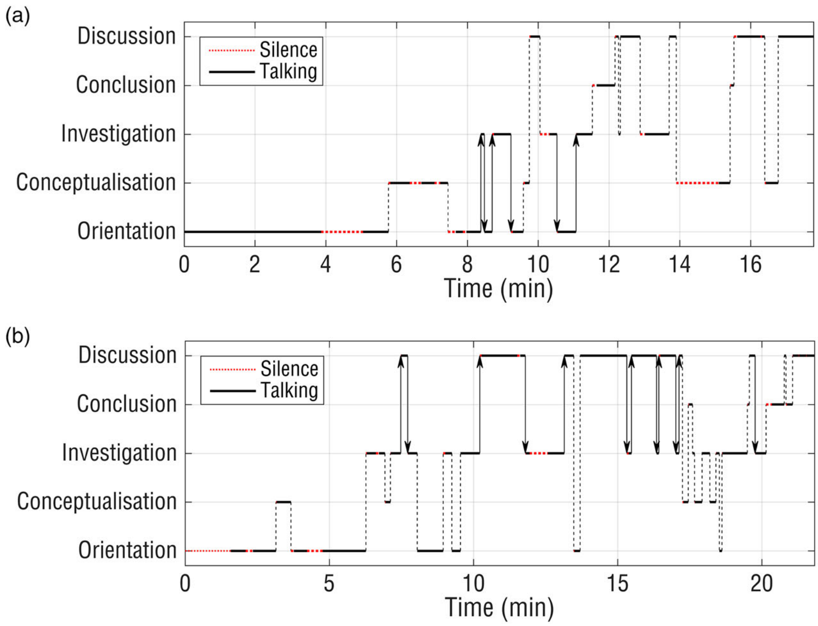

Figure 2. The overall picture of the IBL process of (a) Group 1 and (b) Group 2. The most frequent transitions between the IBL phases are marked with arrows.

visualisations) characterised the CIBL processes. We found that the transitions between the investigation and orientation phases characterised the CIBL process of Group 1, while the most frequent transitions of Group 2 took place between the investigation and discussion phases.

We start by elaborating an example of the most frequent transitions of Group 1 (see Figure 2(a) and Table 6). Here, Petri planned methods (i.e. investigation, see Table 2) that could be used to solve the problem, but Krista showed a misconception[1] in her phrasing of a question (i.e. orientation). Figure 2(a) indicates that the challenge for Group 1 was not the remarkable amount of time they used in the orientation phase, but the effect of the transitions between the investigation and orientation phases on the progress of their CIBL process. Therefore, Group 1 did not properly proceed to the investigation phase (10 utterances or 7% of the utterances). They neither discussed nor thoroughly reflected on their CIBL process before making the last conclusions (10 utterances in the discussion phase before $t = 15.5$ min). Consequently, Group 1 ended up with an incorrect solution.

Table 6. An extract ($t = 10.6$ min in Figure 2(a)), which illustrates the most frequent transitions between the IBL phases in Group 1.

Student	Utterance	Serial number of utterance	Phase of IBL	Utilisation of technological tools
Petri	We should go back and forth, run at least the series of five per distance and then look at the averaged value. Is there any better way [to do that]?	81	Investigation	Deep-level use of technology
Krista	So, the displacement, it is the mean-free path, is it?	82	Orientation	No use of technology

Table 7. An extract (t = 16.5 min in Figure 2(b)), which illustrates the most frequent transitions between the IBL phases in Group 2.

Student	Utterance	Serial number of utterance	Phase of IBL	Utilisation of technological tools
Lasse	I was just about to say that it looks quite linear. However, we get to know if it is like a square root or linear if you set 2000 to the value of N [the number of collisions in the script], for instance.	189	Discussion	Deep-level use of technology
Iida	But it was said that it [the number of collisions] can be 1000 at the most.	190	Discussion	Surface-level use of technology
Vesa	Okay …	191	Discussion	No use of technology
Lasse	Substitute 1000, for example. Now we see how linear it is.	192	Investigation	Deep-level use of technology

The quote presented in Table 7 illustrates the most frequent transition between the investigation and discussion phases in Group 2 (see Figure 2(b)). Here, Lasse elaborated their previous findings (i.e. discussion), which led the group to conduct further experiments (i.e. investigation). Again, the substantial amount of time spent in the discussion and orientation phases might not have been beneficial. Instead, the repetitive patterns in which Group 2 conducted investigations and elaborated their activities in the discussion phase enhanced data collection and interpretation as well as their reflection on the process. Therefore, the most frequent transitions triggered Group 2 to make justified conclusions, which eventually led them to the correct solution.

The most frequent transitions in the CIBL processes were triggered by the technological tools

The utilisation of the technological tools played an important role in terms of the differences between the most frequent transitions of the CIBL processes of the groups. Figure 3 (a) shows that Group 1 experienced challenges utilising the technological tools for data collection (i.e. surface-level use) in the investigation phase, which might have triggered the transitions between the orientation and investigation phases. In contrast, Figure 3 (b) shows that Group 2 utilised the technological tools at the surface level, especially in the investigation phase, which triggered a deep-level use of technology in the discussion phase and vice versa.

An attempt by Group 1 to conduct a technology-enhanced investigation is presented in Table 6 (see Figure 3(a)). Although Petri suggested that statistical methods could be useful, this deep-level use of technology was followed by a technology-free orientation. The transition illustrates challenges in utilising the technological tools at the surface level in the investigation phase, during which the planned activities (deep-level use of technology) should be put into practice. Therefore, Group 1 made conclusions without data supporting any of the proposed options, which led them to an incorrect solution (see, t = 11.7 min in Figure 2(a), utterance 95 in Figure 3(a)).

In addition to utilising the technological tools more frequently, Group 2 enhanced several transitions between the investigation and discussion phases by surface- and deep-level uses of technology. This is demonstrated in the quote presented in Table 7. The quote started after a surface-level use of technology in the investigation phase (data

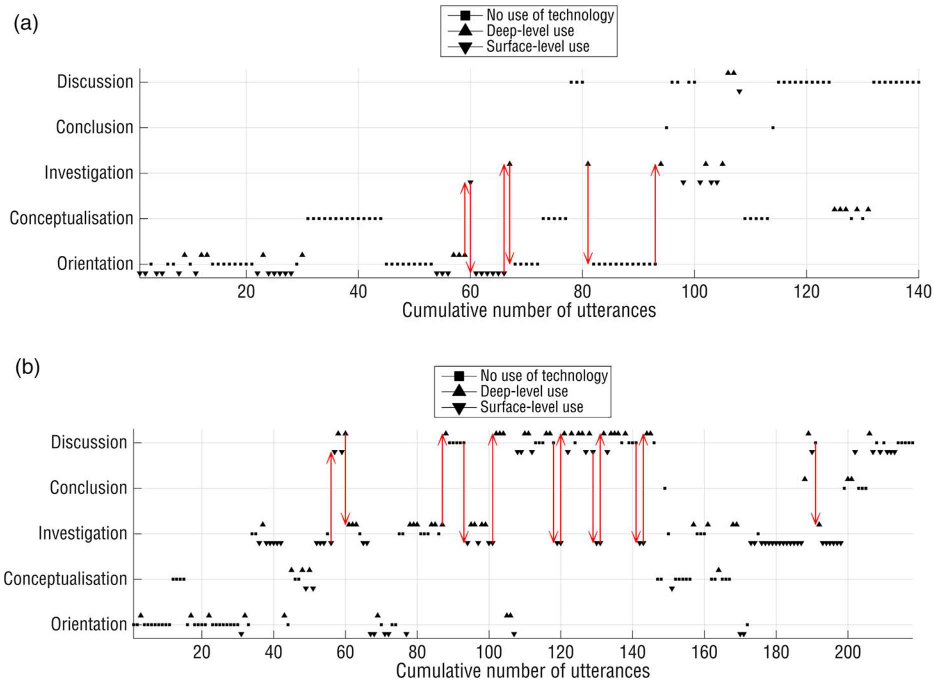

Figure 3. Utilisation of the technological tools in the different IBL phases of (a) Group 1 and (b) Group 2. Symbols represent utterances. The most frequent transitions between the IBL phases are marked with arrows.

collection, see Figure 3(b)), which was followed by deep-level uses of technology in the conclusion and discussion phases. Lasse realised that the square root function might look linear at first and that they should utilise numerical methods to determine the relationship between displacement and time by increasing the value of the number of collisions. Figure 3(b) shows that, through a deep-level use of technology, Group 2 returned to the investigation phase to implement the planned activities into practice (i.e. surface-level use of technology).

Visualisations capture individual students' stable participation inequity

Next, we present what visualisations reveal about individual students' participation in the CIBL processes. First, high participation inequity did not evolve gradually in the groups; rather, it was locked-in at the beginning of the learning process. Second, only a few students played an important role in the most frequent transitions, which characterised the technology-enhanced CIBL processes at the group level.

Group 1

The results in Table 8 show that the participation inequity regarding the cumulative number of utterances was high, and Figure 4(a) shows that the participation inequity was stable. Even if quality over quantity is argued, the sum of the individual students'

Table 8. Group 1: Cumulative number of utterances in the different IBL phases. The cumulative number of utterances referring to the technological learning resources are presented in parentheses.

	Orientation	Conceptualisation	Investigation	Conclusion	Discussion	Sum	%
Petri	26 (11)	13 (3)	8 (8)	1 (0)	10 (2)	58 (24)	41 (51)
Viola	14 (3)	8 (0)	2 (2)	0 (0)	8 (1)	32 (6)	23 (13)
Juha	8 (4)	3 (1)	0 (0)	1 (0)	8 (0)	20 (5)	14 (11)
Krista	11 (4)	7 (1)	0 (0)	0 (0)	1 (0)	19 (5)	14 (11)
Saila	9 (7)	0 (0)	0 (0)	2 (0)	0 (0)	11 (7)	8 (15)
Total	68 (29)	31 (5)	10 (10)	2 (0)	29 (3)	140 (47)	
%	49 (62)	22 (11)	7 (21)	1 (0)	21 (6)		

impact values (see Table 4) was nearly equal to Petri's cumulative value until the group proceeded for the last time to the orientation phase (Figure 4(b)).

Petri's dominance becomes even clearer when considering only the utilisation of technology (Table 8). The visualisation of the overall picture of the technology-enhanced CIBL process (Figure 5) shows that Petri triggered all the transitions to the investigation phase in which technological tools were utilised. However, separate attempts to start a technology-enhanced investigation and to move the group towards the goal of the inquiry (impact value +1) were most frequently followed by orientation. While Petri was also active in the orientation phase, Figure 5 shows that the others participated in the process mainly one by one, without driving the process forward (impact value −1 or 0). High participation inequity might be related to students' inability to utilise the technological tools, as evidenced in Saila's statement ($t = 5.1$ min, utterance 22):

> Saila: I am not able to modify that [the script] at all … Or if you want, so …

Group 2

Despite the productive technology-enhanced CIBL process at the group level (i.e. they solved the inquiry task correctly), participation inequity was high (Table 9) and stable (Figure 6(a)) at the individual level. However, Group 2 contained more students who drove the inquiry forward than Group 1. Figure 6(b) shows that Iida, Vesa and Lasse all contributed to the sum of the impact values. As Iida, Vesa and Lasse impacted the process at somewhat different phases (e.g. Iida at the beginning and at the end of the process, see Figure 7), the sum of the impact values increased rather linearly throughout the CIBL process. This is consistent with the findings of the previous sections: for Group 2, the process was structured (Figure 2(b)), and the group managed to utilise the technology in every phase of the inquiry (Figure 3(b)).

The results in Table 9 show that participation equity depended on the specific IBL phase considered. Specifically, the visualisation of the technology-enhanced CIBL process as a whole (Figure 7) shows that Lasse and Vesa played the most important role in the transitions between the investigation and discussion phases, which characterised the CIBL process at the group level. They were also responsible for elaborating and reflecting on the CIBL process in the discussion phase in a productive way (impact value +1). Iida was active and drove the process forward in the orientation phase, but Figure 7 shows that halfway through, Iida did not take part in the investigation and discussion activities. Eetu and Joakim did not engage in the CIBL process until the investigation phase. Contrary to Group 1, participation inequity in Group 2 was not

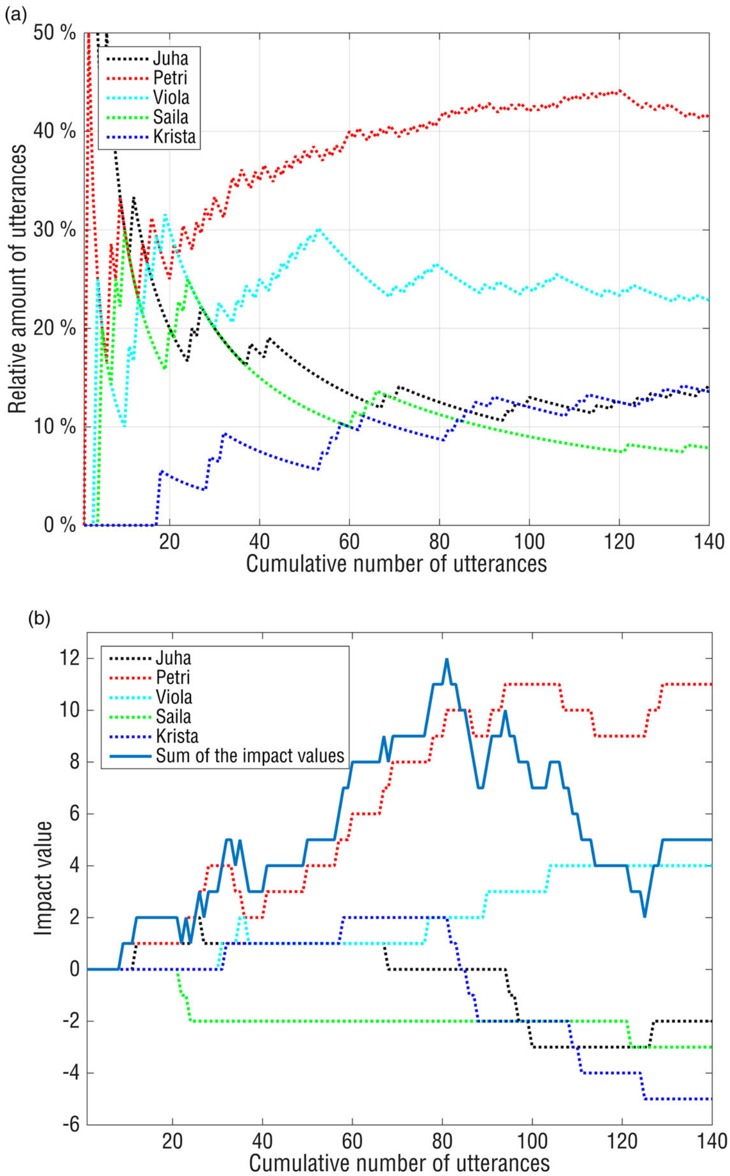

Figure 4. Group 1. (a) Development of participation (in)equity in the collaborative learning process. (b) Development of different students' impact values on the collaborative learning process.

necessarily related to students' inability to utilise the technological tools, as especially Joakim utilised the technological tools in a productive way in the investigation phase (impact value +1).

Conclusions

We used multiple visualisations as a novel method to form a comprehensive picture of technology-enhanced CIBL processes in an authentic higher education learning context.

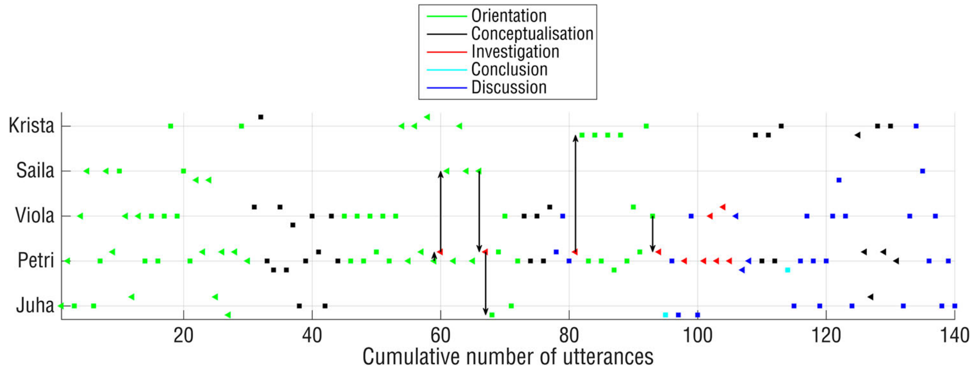

Figure 5. Group 1: The overall picture of the technology-enhanced CIBL process. The IBL phases are marked with different colours. Symbols represent utterances. Triangles indicate utterances that included a reference to the technological tools. The symbol is above/below/on a horizontal axis if the utterance had a positive/negative/no impact (+1/−1/0) on the ongoing interaction. The transitions between the orientation and the investigation phases are marked with arrows.

Table 9. Group 2: Cumulative number of utterances in the different IBL phases; the cumulative number of utterances referring to the technological learning resources are presented in parentheses.

	Orientation	Conceptualisation	Investigation	Conclusion	Discussion	Sum	%
Vesa	16 (6)	9 (3)	17 (15)	0 (0)	25 (16)	67 (40)	31 (31)
Lasse	11 (3)	7 (3)	19 (17)	3 (1)	22 (16)	62 (40)	28 (31)
Iida	16 (7)	9 (1)	15 (12)	4 (1)	4 (2)	48 (23)	22 (18)
Eetu	3 (1)	0 (0)	14 (9)	0 (0)	9 (5)	26 (15)	12 (12)
Joakim	0 (0)	0 (0)	11 (8)	1 (1)	3 (2)	15 (11)	7 (9)
Total	46 (21)	25 (7)	76 (61)	8 (3)	63 (41)	218 (129)	
%	21 (13)	11 (5)	35 (47)	4 (2)	29 (32)		

Table 10 presents the summary of the visualisations used in this study as well as how these visualisations captured different viewpoints of technology-enhanced CIBL processes.

First, we answered the research question ‘What transitions characterise technology-enhanced CIBL processes at the group level?’ We performed thematic analyses based on the phases of IBL (Pedaste et al., 2015) in order to form an overall picture of the IBL processes of two groups (Figure 2). We found that instead of the amount of time the groups spent on a certain IBL phase, the between-group differences of the most frequent transitions between the IBL phases characterised the groups’ technology-enhanced CIBL processes.

To answer the second research question (‘How do the groups utilise technological tools in these transitions?’), we analysed the utilisation of the technological tools and their levels of usage. The visualisations (Figure 3) revealed that the most frequent transitions were triggered by the technological tools. The visualisations show how Group 2 succeeded in utilising technological tools both at the deep (e.g. planning in the discussion phase) and surface levels (e.g. implementation in the investigation phase), while Group 1 could not conduct the planned activities (deep-level use) into practice (surface-level use). This challenge may be explained by numerical analysis methods, which require skills from physics, mathematics, and computer science (Taub, Armoni, Bagno, & Ben-Ari, 2015). To solve the problem, students had to (i) understand the concepts relating to the phenomenon

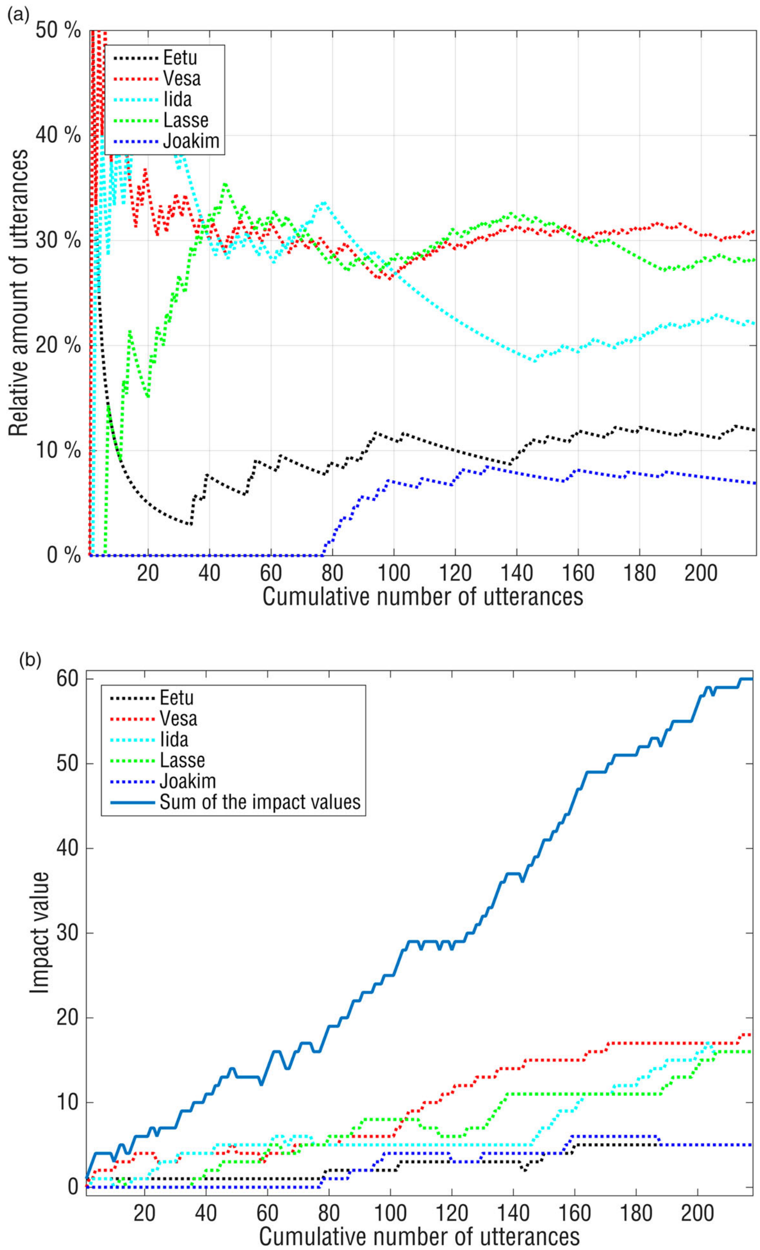

Figure 6. Group 2. (a) Development of participation (in)equity in the collaborative learning process. (b) Development of different students' impact values on the collaborative learning process.

in hand (eg, free mean path, the displacement; physics skills); (ii) understand and overcome the statistical nature of the phenomenon (eg, calculating the average of several values of the displacement; mathematics and physics skills); and (iii) find out how to use the script to overcome the randomness of the phenomenon (eg, adding a loop structure to the script that automatically calculate the average of several values of the

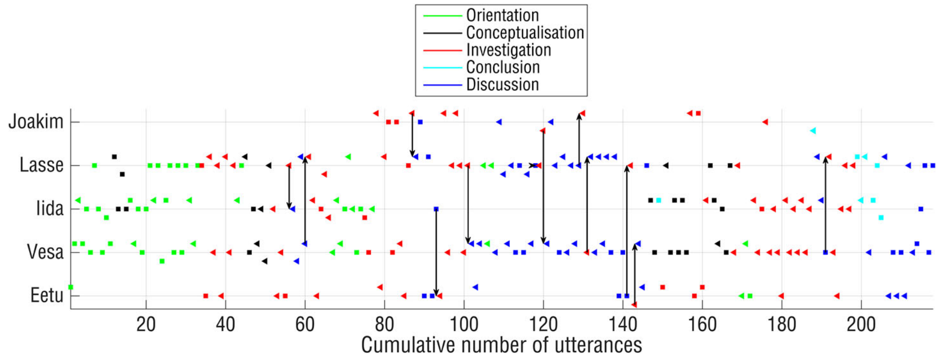

Figure 7. Group 2: The overall picture of the technology-enhanced CIBL process. The IBL phases are marked with different colours. Symbols represent utterances. Triangles indicate utterances that included a reference to the technological tools. The symbol is above/below/on a horizontal axis if the utterance had a positive/negative/no impact (+1/−1/0) on the ongoing interaction. The transitions between the investigation and the discussion phases are marked with arrows.

displacement; computer science skills). As similar challenges have also been reported in collaborative uses of computer simulations (Chang et al., 2017), it is vital to find ways to engage all students in the productive use of technological resources, regardless of the type of tool (Jeong & Hmelo-Silver, 2010).

Third, we addressed the question 'What do visualisations reveal about individual students' participation in technology-enhanced CIBL processes?' We focussed on collaborative learning, which was analysed not only in terms of frequency of contributions (Figures 4(a) and 6(a)), but also in terms of impact (Figures 4(b) and 6(b); Kapur et al., 2008). We also synthesised the viewpoints of IBL, technology enhancement and collaborative learning (Figures 5 and 7), which showed the phases in which the students were able to participate and impact the learning processes as well as how they succeeded in utilising the technological tools in the different IBL phases. Despite the differences in the CIBL processes at the group levels (Figures 2 and 3), the groups had similar challenges at the individual level (Figures 4–7; see Klette, 2009). Regarding the frequency of contributions, their impact and the most frequent transitions, we found students from both groups who barely contributed to the CIBL process. Even if the phase of IBL had an effect on the students' readiness to participate in the CIBL process, the visualisations (Figures 4(a) and 6(a)) captured stable participation inequity throughout the CIBL processes. Kapur and colleagues (2008) used

Table 10. Summary of how the visualisations relate to different viewpoints of learning processes.

Figure(s)	Visualisation	Inquiry-based learning	Technology-enhancement	Collaborative learning
2	The overall picture of an IBL process	X		
3	The utilisation of the technological tools in the different IBL phases	X	X	
4a and 6a	The development of participation (in)equity in a collaborative learning process			X
4b and 6b	The development of different students' impact on a collaborative learning process			X
5 and 7	The overall picture of a technology-enhanced CIBL process	X	X	X

this notion in the context of text-based synchronous online chat discussions, but our findings suggest that rapidly stabilised participation inequity may not depend on the form of interaction, i.e. whether face-to-face or computer-mediated communication.

In sum, visualisations provide a compact and accessible way to illustrate complex technology-enhanced CIBL processes from various viewpoints. This kind of analysis increases the understanding of collaborative inquiry activities as well as raises topics for future research. Teachers can use visualisations as a tool to analyse how students follow designed technology-enhanced collaborative inquiry activities. Specifically, the visualisations (as presented in Figures 5 and 7) can help with implementing even individually tailored scaffolds as we can analyse the challenges of an individual student in (i) participating in the specific phases of IBL; (ii) using the technological tools and the information provided by the tools in inquiry-based activities; and (iii) impacting the joint IBL process in a productive way.

Discussion

We hypothesised that the use of visualisations reveal which IBL phases need scaffolds so as to involve different groups and group members in productive working processes in TEL settings. During the orientation, students should not only clarify the key concepts of an assignment (Figure 2), but should also become familiar with the technological tools provided (Figures 3, 5 and 7). To achieve the goals of the conceptualisation phase, students could be encouraged to state in the TEL environment common research questions or hypotheses and write out plans for addressing these. This could make the properties of the technological tools and the planned procedure visible to everyone. Previous research has also highlighted the significance of scaffolding in the conceptualisation phase (Wang et al., 2014) and providing written explanations (Koretsky, Brooks, & Higgins, 2016). Additionally, scaffolds focussing on interaction should be implemented at the beginning of the inquiry, before high participation inequity among students are locked-in (Figures 4 and 6). To improve participation equity, integrating, e.g. collaborative scripts (Kobbe et al., 2007), into the TEL environment could be fruitful for collaboration. In our case, each student could be scripted to be responsible for a phase of IBL (five students and five phases of IBL).

This study was an attempt at seeking new ways of visualising technology-enhanced CIBL processes. One major limitation of our approach is that our analysis focussed only on two small groups that sought to solve a thermodynamics problem. Based on the teaching experience in the course (the first and the third author of this study), we assume that the challenges of Groups 1 and 2 were not unique but the similar problems arose in other groups and in different problems as well. However, more research is needed before generalisation of the findings. Second, despite the observed differences between the groups, background factors (e.g. sociodemographic variables, gender, major; Nehring, Nowak, zu Belzen, & Tiemann, 2015) may have played a role in the failure of Group 1 and the success of Group 2. Finally, the students could have contributed to the CIBL processes in ways that were not visible in screen-captures and audio recordings (such as scribbling diagrams on a paper or making hand gestures), as we wanted to collect data from authentic learning contexts without interfering with students through the presence of researchers, instructors or additional equipment.

Despite these limitations, our study has several strengths. First, we provide a methodological contribution to the field, analysing how students' technology-enhanced inquiry and collaboration skills appear in authentic higher education learning contexts. New methods to analyse how productive technology-enhanced CIBL processes emerge are needed (Mercer, 2008; Stahl, 2017), as implementing technology-enhanced collaborative inquiry to curriculums requires the integration of theoretical, pedagogic and technological development (Hämäläinen & Vähäsantanen, 2011). Second, this kind of analytical technique, which focuses on certain viewpoints of complex technology-enhanced CIBL processes, can help both researchers and teachers in designing specific scaffolds for students in particular contexts. Third, our methodological approach provides tools for researchers and teachers to analyse the kind of role that designed scaffolds or instructional interventions play in students' learning processes. Finally, when the need to present information in a more compact way increases with growing amounts of data from learning processes, visualisations may prove useful in terms of coping with this increased volume. Novel and multimodal data-capturing methods could even enable the visualisation of ongoing technology-enhanced CIBL processes. This might make students more aware of their inquiry and collaboration skills, as currently, feedback places greater emphasis on content-related expertise (Blikstein & Worsley, 2016).

It is evident that science education needs new teaching and learning practices, as traditional elements such as lectures (Arthurs & Kreager, 2017; Freeman et al., 2014) and labs (Holmes, Olsen, Thomas, & Wieman, 2017) may not prepare students for the challenges of the twenty-first century (Ding, Wei, & Mollohan, 2016; Matthews, Firn, Schmidt, & Whelan, 2017). This research focussed on physics learning, but our methodological approach is also applicable to learning in other subjects. In the future, visualisations can be utilised in various contexts to reveal challenges concerning students' inquiry, technological and collaborative skills. Our methodological approach can also be extended to other important twenty-first century skills such as scientific reasoning.

Note

1. The displacement is the vector between the start and end points of an atom after it has collided N times. After each collision, an atom moves (on average) a mean-free path (scalar quantity) to a random direction (see Figure 1(a,b)).

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References

Alfieri, L., Brooks, P. J., Aldrich, N. J., & Tenenbaum, H. R. (2011). Does discovery-based instruction enhance learning? *Journal of Educational Psychology*, *103*(1), 1–18.
Arthurs, L. A., & Kreager, B. Z. (2017). An integrative review of in-class activities that enable active learning in college science classroom settings. *International Journal of Science Education*, *39*(15), 2073–2091.
Balgopal, M. M., Casper, A. M. A., Atadero, R. A., & Rambo-Hernandez, K. (2017). Responses to different types of inquiry prompts: College students' discourse, performance, and perceptions of group work in an engineering class. *International Journal of Science Education*, *39*(12), 1625–1647.
Bell, T., Urhahne, D., Schanze, S., & Ploetzner, R. (2010). Collaborative inquiry learning: Models, tools, and challenges. *International Journal of Science Education*, *32*(3), 349–377.
Blikstein, P., & Worsley, M. (2016). Multimodal learning analytics and education data mining: Using computational technologies to measure complex learning tasks. *Journal of Learning Analytics*, *3*(2), 220–238.
Braun, V., & Clarke, V. (2006). Using thematic analysis in psychology. *Qualitative Research in Psychology*, *3*(2), 77–101.
Bush, D., Sieber, R., Seiler, G., & Chandler, M. (2017). University-level teaching of anthropogenic global climate change (AGCC) via student inquiry. *Studies in Science Education*, *53*(2), 113–136.
Çelik, H., & Pektaş, H. (2017). Graphic comprehension and interpretation skills of preservice teachers with different learning approaches in a technology-aided learning environment. *International Journal of Science and Mathematics Education*, *15*(1), 1–17.
Chang, C.-J., Chang, M.-H., Liu, C.-C., Chiu, B.-C., Fan Chiang, S.-H., Wen, C.-T., … Chai, C.-S. (2017). An analysis of collaborative problem-solving activities mediated by individual-based and collaborative computer simulations. *Journal of Computer Assisted Learning*, *33*(6), 649–662.
de Jong, T., & Ferguson-Hessler, M. (1996). Types and qualities of knowledge. *Educational Psychologist*, *31*(2), 105–113.
De Wever, B., Hämäläinen, R., Voet, M., & Gielen, M. (2015). A wiki task for first-year university students: The effect of scripting students' collaboration. *The Internet and Higher Education*, *25*, 37–44.
Ding, L., Wei, X., & Mollohan, K. (2016). Does higher education improve student scientific reasoning skills? *International Journal of Science and Mathematics Education*, *14*(4), 619–634.
Freeman, S., Eddy, S. L., McDonoug, M., Smith, M. K., Okoroafor, N., Jordt, H., & Wenderoth, M. P. (2014). Active learning increases student performance in science, engineering, and mathematics. *Proceedings of the National Academy of Sciences*, *111*(23), 8410–8415.
Hämäläinen, R., & Arvaja, M. (2009). Scripted collaboration and group-based variations in a higher education CSCL context. *Scandinavian Journal of Educational Research*, *53*(1), 1–16.
Hämäläinen, R., & Vähäsantanen, K. (2011). Theoretical and pedagogical perspectives on orchestrating creativity and collaborative learning. *Educational Research Review*, *6*(3), 169–184.
Hmelo-Silver, C., Jeong, C., Faulkner, R., & Hartley, K. (2017). *Computer-supported collaborative learning in STEM domains: Towards a meta-synthesis*. Proceedings of the 50th Hawaii International Conference on System Sciences.
Holmes, N. G., Olsen, J., Thomas, J. L., & Wieman, C. E. (2017). Value added or misattributed? A multi-institution study on the educational benefit of labs for reinforcing physics content. *Physical Review Physics Education Research*, *13*(1), 010129-1–010129-12.

Jensen, J. L., & Lawson, A. (2011). Effects of collaborative group composition and inquiry instruction on reasoning gains and achievement in undergraduate biology. *CBE – Life Science Education*, *10*(1), 64–73.

Jeong, H., & Hmelo-Silver, C. E. (2010). Productive use of learning resources in an online problem-based learning environment. *Computers in Human Behavior*, *26*(1), 84–99.

Kapur, M. (2011). Temporality matters: Advancing a method for analyzing problem-solving processes in a computer-supported collaborative environment. *International Journal of Computer-Supported Collaborative Learning*, *6*(1), 39–56.

Kapur, M., Voiklis, J., & Kinzer, C. K. (2008). Sensitivities to early exchange in synchronous computer-supported collaborative learning (CSCL) groups. *Computers & Education*, *51*(1), 54–66.

Klette, K. (2009). Challenges in strategies for complexity reduction in video studies. Experiences from the PISA+ study: A video study of teaching and learning in Norway. In T. Janik & T. Seidel (Eds.), *The power of video studies in investigating teaching and learning in the classroom* (pp. 61–82). New York, NY: Waxmann Publishing.

Knight, R. D. (2014). *Physics for scientists and engineers: A strategic approach with modern physics* (3rd ed.). Harlow: Pearson Education.

Kobbe, L., Weinberger, A., Dillenbourg, P., Harrer, A., Hämäläinen, R., Häkkinen, P., & Fischer, F. (2007). Specifying computer-supported collaboration scripts. *International Journal of Computer-Supported Collaborative Learning*, *2*(2), 211–224.

Koretsky, M. D., Brooks, B. J., & Higgins, A. Z. (2016). Written justifications to multiple-choice concept questions during active learning in class. *International Journal of Science Education*, *38*(11), 1747–1765.

Koskinen, P., Lämsä, J., Maunuksela, J., Hämäläinen, R., & Viiri, J. (2018). Primetime learning: Collaborative and technology-enhanced studying with genuine teacher presence. *International Journal of STEM Education*, *5*(20), 1–13.

Krathwohl, D. R. (2002). A revision of Bloom's taxonomy: An overview. *Theory into Practice*, *41*(4), 212–218.

Krippendorff, K. (2004). *Content analysis: An introduction to its methodology* (2nd ed.). Thousand Oaks, CA: Sage.

Lazonder, A., & Harmsen, R. (2016). Meta-analysis of inquiry-based learning: Effects of guidance. *Review of Educational Research*, *86*(3), 681–718.

Leinonen, R., Asikainen, M. A., & Hirvonen, P. E. (2017). Peer discussions in lecture-based tutorials in introductory physics. *Physical Review Physics Education Research*, *13*(1), 010114-1–010114-13.

Matthews, K. E., Firn, J., Schmidt, S., & Whelan, K. (2017). A comparative study on student perceptions of their learning outcomes in undergraduate science degree programmes with differing curriculum models. *International Journal of Science Education*, *39*(6), 742–760.

Mercer, N. (2008). The seeds of time: Why classroom dialogue needs a temporal analysis. *Journal of the Learning Sciences*, *17*(1), 33–59.

Nehring, A., Nowak, K. H., zu Belzen, A. U., & Tiemann, R. (2015). Predicting students' skills in the context of scientific inquiry with cognitive, motivational, and sociodemographic variables. *International Journal of Science Education*, *37*(9), 1343–1363.

Pedaste, M., Mäeots, M., Siiman, L. A., de Jong, T., van Riesen, S. A. N., Kamp, E. T., … Tsourlidaki, E. (2015). Phases of inquiry-based learning: Definitions and the inquiry cycle. *Educational Research Review*, *14*, 47–61.

Perkins, K., Adams, W., Dubson, M., Finkelstein, N., Reid, S., Wieman, C., & LeMaster, R. (2006). Phet: Interactive simulations for teaching and learning physics. *The Physics Teacher*, *44*(1), 18–23.

Rau, M. A., Bowman, H. E., & Moore, J. W. (2017). An adaptive collaboration script for learning with multiple visual representations in chemistry. *Computers & Education*, *109*, 38–55.

Sins, P. H. M., Savelsbergh, E. R., van Joolingen, W. R., & van Hout-Wolters, B. H. A. M. (2011). Effects of face-to-face versus chat communication on performance in a collaborative inquiry modeling task. *Computers & Education*, *56*(2), 379–387.

Stahl, G. (2017). Group practices: A new way of viewing CSCL. *International Journal of Computer-Supported Collaborative Learning*, *12*(1), 113–126.
Summers, M., & Volet, S. (2010). Group work does not necessarily equal collaborative learning: Evidence from observations and self-reports. *European Journal of Psychology of Education*, *25*(4), 473–492.
Taub, R., Armoni, M., Bagno, E., & Ben-Ari, M. (2015). The effect of computer science on physics learning in a computational science environment. *Computers & Education*, *87*, 10–23.
Thompson, K., Ashe, D., Carvalho, L., Goodyear, P., Kelly, N., & Parisio, M. (2013). Processing and visualizing data in complex learning environments. *American Behavioral Scientist*, *57*(10), 1401–1420.
Wagh, A., Cook-Whitt, K., & Wilensky, U. (2017). Bridging inquiry-based science and constructionism: Exploring the alignment between students tinkering with code of computational models and goals of inquiry. *Journal of Research in Science Teaching*, *54*(5), 615–641.
Wang, H., Duh, H., Li, N., Lin, T., & Tsai, C. (2014). An investigation of university students' collaborative inquiry learning behaviors in an augmented reality simulation and a traditional simulation. *Journal of Science Education and Technology*, *23*(5), 682–691.
Williams, G., & Clement, J. (2015). Identifying multiple levels of discussion-based teaching strategies for constructing scientific models. *International Journal of Science Education*, *37*(1), 82–107.