UNIVERSITY OF JYVÄSKYLÄ
FACULTY OF EDUCATION AND PSYCHOLOGY

JYU DISSERTATIONS 245

Developing the temporal analysis for computer-supported collaborative learning in the context of scaffolded inquiry

Joni Lämsä

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Esitetään Jyväskylän yliopiston kasvatustieteiden ja psykologian tiedekunnan suostumuksella julkisesti tarkastettavaksi päärakennuksen salissa C4 syyskuun 19. päivänä 2020 kello 12.

Academic dissertation to be publicly discussed, by permission of the Faculty of Education and Psychology of the University of Jyväskylä, in Main Building, lecture hall C4, on September 19, at 12 o'clock noon.

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ABSTRACT

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Computer-supported collaborative learning (CSCL) frequently takes the form of inquiry-based learning (IBL) in science education. To achieve the benefits of computer-supported collaborative inquiry-based learning (CSCIL), various scaffolds have been studied from the perspective of *what* (not *how*) learning occurs and *what* (not *how*) differences emerge between the scaffolded and non-scaffolded conditions. To better address the *how* questions, my theoretical aim was to develop a temporal analysis procedure for CSCL. Based on a systematic literature review of 78 journal papers, I defined six key operations for the analysis of CSCL's temporal aspects: proposing research aims regarding the temporal aspects, setting up the context, collecting process data, conceptualising events, conducting temporal analysis methods and interpreting the outcomes. A study of how the included papers performed these operations showed how the researchers implicitly conceptualised the temporal aspects of CSCL when focusing on the characteristics of or interrelations between events over time.

My methodological aim was to advance temporal analysis methods to study CSCIL. My empirical aim was to design scaffolds and analyse their role in CSCIL by employing the key operations and advanced methods when groups used a numerical problem-solving tool (Python program) to inquire in undergraduate physics courses. To study *how* CSCIL occurs, I used video data and visualised the transitions between the IBL phases (i.e. IBL sequences) and groups' ways of using the Python program for inquiry over time (two groups, n = 10). The identified challenges and productive practices guided the scaffold design. To study *how* differences emerge between the conditions (46 groups, N = 231), I performed temporal log data analysis (TLDA) and temporal lag sequential analysis (TLSA). Temporal distinctions in how the groups used the Python program between the conditions (captured by TLDA) were associated with the differences in the content and temporal emergence of IBL sequence clusters between the conditions (captured by TLSA of video data). This dissertation demonstrates how temporal analysis may advance our understanding of the premises for successful learning and benefit the design and implementation of scaffolds.

Keywords: computer-supported collaborative learning, inquiry-based learning, scaffolding, temporal analysis

TIIVISTELMÄ (ABSTRACT IN FINNISH)

Lämsä, Joni
Teknologiatuettu yhteisöllinen tutkiva oppiminen: ajallisen tarkastelun näkökulma
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Luonnontieteiden opetuksessa on hyödynnetty pitkään tietokoneavusteista yhteisöllistä tutkivaa oppimista (eng. computer-supported collaborative inquiry-based learning, CSCIL), jota varten on kehitetty erilaisia tukimuotoja. Tutkimus on tyypillisesti keskittynyt siihen, *mitä* oppimistuloksia saavutetaan tiettyä tukimuotoa käytettäessä. Vähemmälle huomiolle on jäänyt, *miten* oppiminen tapahtuu ja *miten* erot tuettujen ja ei-tuettujen ryhmien välille syntyvät. Tutkimukseni tavoitteena oli vastata tähän haasteeseen ja tuottaa uutta tietoa siitä, miten CSCIL:ää voidaan tarkastella ajallisesti. Määritin 78 artikkelia sisältävän systemaattisen kirjallisuuskatsauksen perusteella menettelytavan tietokoneavusteisen yhteisöllisen oppimisen ajalliseen tarkasteluun. Menettelytapa sisälsi kuusi avainoperaatiota: 1) ajallisiin näkökulmiin keskittyvien tutkimuskysymysten muotoileminen, 2) tutkimuksen kontekstin määrittäminen, 3) prosessiaineiston kerääminen, 4) tapahtumien käsitteellistäminen, 5) ajallisten analyysimenetelmien toteuttaminen ja 6) tulosten tulkitseminen.

Metodologinen tavoitteeni oli sellaisten uusien ajallisten analyysimenetelmien kehittäminen, joiden avulla erityisesti CSCIL:ää voidaan tarkastella. Lisäksi tavoitteenani oli tukimuotojen suunnittelu ja niiden roolien tarkastelu CSCIL:ssä hyödyntämällä määrittelemiäni avainoperaatioita ja kehittämiäni menetelmiä. Tarkastelin yliopistofysiikan peruskursseilla opiskelijaryhmiä, jotka käyttivät Python-ohjelmaa tutkivan oppimisen ongelman ratkaisemiseen. Tutkin videoaineistosta CSCIL:ää visualisoimalla ryhmien tutkivan oppimisen ketjuja (eli siirtymiä tutkivan oppimisen vaiheiden välillä) ja tapoja hyödyntää Python-ohjelmaa ajan edetessä (kaksi ryhmää, n = 10). Ryhmissä ilmenneiden haasteiden perusteella suunnittelin ja lisäsin ryhmille tukimuotoja teknologiseen oppimisympäristöön. Seuraavaksi tarkastelin, *miten* erot tuettujen ja ei-tuettujen ryhmien välille syntyivät ajan edetessä (46 ryhmää, N = 231). Analysoin oppimisympäristöön kertyvän lokiaineiston avulla eroja Python-ohjelman hyödyntämisessä tuettujen ja ei-tuettujen ryhmien välillä. Videoaineiston perusteella nämä erot olivat yhteydessä tutkivan oppimisen ketjuryppäiden sisältöön ja siihen, missä vaiheessa oppimisprosessia nämä ryppäät keskimäärin ilmenivät. Tutkimukseni mukaan täydentämällä kasvatustieteissä vakiintunutta muuttujiin ja niiden vaihteluun perustuvaa tilastollista päättelyä (*mitä* opitaan) oppimisen ajallisella tarkastelulla (*miten* opitaan) voimme ymmärtää paremmin hyvän oppimisen ja sen oikea-aikaisen tukemisen lähtökohtia.

Asiasanat: ajallinen tarkastelu, oppimisen tukeminen, teknologiatuettu oppiminen, tietokoneavusteinen oppiminen, tutkiva oppiminen, yhteisöllinen oppiminen

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Jyväskylässä ja Oulussa juhannuksen tienoilla 2020
Jyväskylä and Oulu, June 2020

Joni Lämsä

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Sub-study II	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.
Sub-study III	Lämsä, J., Hämäläinen, R., Koskinen, P., & Viiri, J. (2018). Visualising the temporal aspects of collaborative inquiry-based learning processes in technology-enhanced physics learning. *International Journal of Science Education*, *40*(14), 1697–1717.
Sub-study IV	Lämsä, J., Hämäläinen, R., Koskinen, P., Viiri, J., & Mannonen, J. (2020). The potential of temporal analysis: Combining log data and lag sequential analysis to investigate temporal differences between scaffolded and non-scaffolded group inquiry-based learning processes. *Computers & Education*, *143*, 103674.

I was the first author of sub-studies I, III and IV and was responsible for writing these manuscripts. In sub-study I, I was responsible for the systematic literature review and theoretical development. In sub-studies III and IV, I planned and conducted the data collection, was responsible for the methodology and its development and searched for the literature. I have an MSc degree (physics), which enabled me to interpret the findings of sub-studies III and IV. The co-writers had advisory roles in commenting on sub-studies I, III and IV. In sub-study II, I contributed to writing the theoretical background of the primetime learning model and to structuring the manuscript. I also participated in revising the manuscript to its final form.

1 INTRODUCTION

The learning and teaching of natural sciences in universities are facing challenges. On the one hand, we increasingly need people with an in-depth knowledge of natural sciences and versatile problem-solving skills who can provide solutions to complex problems such as climate change. On the other hand, natural sciences are not on the top of the lists from which the youth choose their disciplines. Even more worrying, however, are the poor retention and high dropout rates amongst those people who start studying natural sciences (Education Statistics Finland, 2020; van den Hurk et al., 2019). To address the challenges of the retention and dropout rates, novel learning and teaching approaches are needed. At the University of Jyväskylä, we have developed and implemented the primetime learning model in basic-level physics courses since autumn 2016 (sub-study II).

The primetime learning model comprises the principles, practice, problem-solving and primetime phases; thus, there are neither lectures nor end-of-course exams in the courses. At the beginning of the courses, the students are divided into groups of 4–6 students. Each week of the courses starts with the principles phase, in which the students self-study the selected physics principles for the week in a technological learning environment. Next, in the practice phase, the groups schedule time and a place, and they collaboratively solve problems face-to-face in the technological learning environment with a shared laptop computer; there is no teacher. In the problem-solving phase, each student solves full-scale quantitative physics problems so that they can collaborate with their peers or ask for help from a teacher. Each week ends with the primetime phase, in which one group and the teacher meet to discuss the challenges faced by the group (see more details in sub-study II). The needed teaching resources are comparable with the 'traditional' lecture-driven approaches; however, the resources are used in the intimate primetime meetings between a teacher and group of students to enhance academic and social integration (Tinto, 1975; see also Ulriksen et al., 2010; van der Zanden et al., 2018). Overall, the primetime learning model seems to be a promising approach because our findings indicate that the model may increase students' retention rates, decrease dropout rates and maintain good learning outcomes (sub-study II).

This dissertation integrates the research-based development of the primetime learning model, particularly its practice phase. The practice phase aims to improve students' conceptual knowledge – that is, to enhance their ability to capture relationships amongst concepts, principles and procedures (de Jong, 2019). To achieve these aims, students are given different technological resources for solving inquiry problems. Computer-supported collaborative inquiry-based learning (CSCIL) is a technologically facilitated and mediated negotiation process amongst individuals (Tan, 2018), in which problems are solved following the practices of scientists (Pedaste et al., 2015). Although CSCIL has been implemented since a long time (e.g. Lipponen & Hakkarainen, 1997; Suthers et al., 1997), it remains a potential and popular way to enhance the knowledge and processes beneficial for modern natural scientists (Jeong et al., 2019).

To achieve the advantages of CSCIL, however, researchers widely agree that students need guidance (Alfieri et al., 2011; Bell et al., 2010; de Jong & Lazonder, 2014). In the practice phase of the primetime learning model, guidance for CSCIL can be provided in the form of scaffolds implemented into the technological learning environment (see e.g. Kim & Hannafin, 2011; Quintana et al., 2004) because a teacher is not present. Researchers have examined the various scaffolds for CSCIL from the viewpoint of *what* learning occurs (see comprehensive review in Zacharia et al., 2015) and *what* differences emerge amongst the scaffolded conditions (e.g. Fang et al., 2016; Kollar et al., 2007) or between the scaffolded and non-scaffolded conditions (e.g. Gijlers et al., 2009; Raes et al., 2012). Although such studies are needed, they could be complemented by investigating *how* learning occurs and *how* differences emerge amongst the different conditions (see Stahl, 2017). By addressing these *how* questions, we might be able to design, test, refine and re-implement scaffolds to further enhance CSCIL.

In computer-supported collaborative learning (CSCL) research, temporal analysis is considered a promising approach to address these types of *how* questions (Ludvigsen et al., 2018). The temporal analysis of CSCL has gained growing interest, expectations and even hype, but the current studies are partly incomparable and incommensurable owing to the lack of established practices for analysing the temporal aspects of CSCL (Knight et al., 2017; Molenaar, 2014). Moreover, few studies have investigated the temporal aspects of CSCIL regardless of the popularity of inquiry-based learning (IBL) in CSCL settings (some exceptions are Chiang et al., 2014; Wang et al., 2014). Even less attention has been paid to the temporal aspects of scaffolded CSCIL, although the need for scaffolding has generally been acknowledged.

In this dissertation, I aim to develop the temporal analysis for CSCL in the context of scaffolded inquiry. My theoretical aim is to develop a temporal analysis procedure for CSCL that includes key operations for analysing its temporal aspects (sub-study I). My methodological aim is to advance temporal analysis methods to study CSCIL (sub-studies III and IV) so that groups' CSCIL processes in the practice phase of the primetime learning model can be better understood (sub-study II). My empirical aim is to design scaffolds and analyse their role in CSCIL in the practice phase of the primetime learning model by employing the temporal analysis procedure and advanced methods. First, to design scaffolds, I studied *how* CSCIL occurs in the practice phase (sub-study III). Second, to analyse the role of the designed scaffolds in the CSCIL processes, I studied *how* differences emerge between the scaffolded and non-scaffolded conditions (sub-study IV). Thus, the outcomes of my study can be used to further develop the primetime learning model, particularly its practice phase.

This paper is divided into seven sections. In section 1, I introduced the research. In sections 2 and 3, I provide the theoretical and methodological frameworks of my study. Section 4 presents the theoretical (section 4.1), methodological and empirical aims (section 4.2). In section 5, I address the theoretical aim and introduce a temporal analysis procedure for CSCL based on a systematic literature review. The procedure forms the basis for achieving the methodological and empirical aims. In section 6, I address the methodological and empirical aims in the practice phase of the primetime learning model. Moreover, I apply the temporal analysis procedure and advance methods for analysing temporal aspects in the context of scaffolded CSCIL. In section 6.1, I visualise the temporal aspects of CSCIL that form the basis for designing scaffolds for CSCIL. In section 6.2, I conduct temporal log data analysis (TLDA) and temporal lag sequential analysis (TLSA) to examine the temporal similarities and differences between non-scaffolded and scaffolded CSCIL. In section 7, I discuss and reflect on the main outcomes and implications of my study. In section 8, I offer my conclusions based on the study's findings.

2 THEORETICAL FRAMEWORK

In this section, I present the theoretical framework for this dissertation. I define CSCL and cover it from the viewpoint of science education, in which IBL is a popular pedagogical approach. After discussing scaffolding CSCIL, I conclude the section with an overview of the prevalent lines of CSCL research.

2.1 Computer-supported collaborative learning (CSCL)

I define CSCL as a triad structure of collaboration in which technological resources support, facilitate and mediate the interaction between two or more learners who aim to achieve a learning goal together (Ludvigsen & Steier, 2019, p. 415; Stahl et al., 2014a). First, collaborative learning can be seen as a compilation of (i) shared learning processes [such as knowledge building (Khanlari et al., 2017), constructing group cognition (Stahl, 2017) and knowledge construction (Ludvigsen, 2016)] and (ii) shared learning activities [such as negotiation of shared meanings (Pea, 1993), elaboration and co-elaboration (Lund, 2019) and argumentation (Noroozi et al., 2012)] (see Hämäläinen & Vähäsantanen, 2011). The shared learning processes and activities and working *together* set collaborative learning apart from cooperative learning, in which learners 'split the work' and 'solve sub-tasks individually' (Dillenbourg, 1999, p. 8). Second, technological resources create 'dynamic conditions' for what happens in collaborative learning (Ludvigsen & Steier, 2019, p. 4). However, collaborative learning alone in technology-enhanced settings does not automatically produce learning; the quality of the shared learning processes and activities affect the outcomes of CSCL (Hämäläinen & Vähäsantanen, 2011). One ultimate goal of the research on CSCL is to understand these processes and activities (Cress et al., 2019) and how to design technological resources to successfully support, facilitate and mediate the processes and activities (Stahl et al., 2014b).

Since the development of CSCL in the 1990s, research on it has included a range of theories, technologies and methodologies (Stahl et al., 2014a). CSCL has also been implemented in various contexts with a variety of pedagogical approaches and has been extensively used in science education (Jeong et al., 2019). Jeong et al. (2019) noted in their meta-analysis that IBL has been one of the most popular pedagogical approaches when CSCL is used in science education and its related disciplines. The popularity of IBL is not surprising because formulating problems and investigating them, which is at the core of IBL (de Jong, 2019), has become increasingly important in today's society (Ludvigsen & Steier, 2019). In this study, collaborative IBL took place in face-to-face interactions without a teacher present; thus, the groups solved inquiry problems by jointly building on others' ideas and thoughts in the practice phase of the primetime learning model (sub-study II). Technological resources facilitated and mediated the collaborative IBL; learning to use technological resources in inquiry was also desirable. The optimal group size is a controversial issue (Fu & Hwang, 2018); however, in this study, to make the groups adaptable to occasional non-attendance and possible dropouts when the groups remained the same throughout the courses, the groups had 4–6 students. In this case, the number of groups was manageable with the available teaching resources. Next, I briefly relate how I define IBL in CSCL settings in this study.

2.1.1 Computer-supported collaborative inquiry-based learning

Studies on CSCIL lie between CSCL and IBL. I define and use IBL as a pedagogical approach in which students apply the practices used by scientists for problem-solving (Keselman, 2003). Accordingly, I examined IBL as a process in which students have a scientific question (de Jong, 2019) and engage in the scientific practices needed to address the question (Keselman, 2003). These practices include, for example, familiarising themselves with the topic of the question and collecting and interpreting empirical data to answer it (Quintana et al., 2004). Various models for IBL have been proposed based on the different structuring of these practices (e.g. Bybee et al., 2006; White & Frederiksen, 1998). These models have also been synthesised (Bell et al., 2010; Pedaste et al., 2015; Rönnebeck et al., 2016). In this study, I relied on the IBL cycle and framework developed by Pedaste et al. (2015), who divided the essential aspects of IBL into five general phases.

In the framework developed by Pedaste et al. (2015), the first IBL phase is *orientation*, in which students familiarise themselves with both the given assignment, including its main variables, and the available learning resources (such as technologies). The second IBL phase is *conceptualisation*, which is divided into two sub-phases: first, students can propose research questions; and second, they can generate hypotheses, which they then begin investigating. The identification of dependent and independent variables is crucial in both sub-phases. The third IBL phase is *investigation*, which is divided into three sub-phases: first, students can explore the problem by planning the data collection process based on a research question; second, students can experiment by formulating and implementing a plan to test a hypothesis; and third, students can analyse and interpret the data. The fourth IBL phase is *conclusion*, in which students provide solutions to the questions or confirm whether the data support the hypotheses. The fifth phase is *discussion*, which is divided into two sub-phases: first, students may communicate their findings and conclusions as well as receive feedback from others; and second, students can reflect on their IBL progress throughout the process ('reflection-in-action') or at the end of the process ('reflection-on-action'; Pedaste et al., 2015, p. 57).

In this study, I did not expect students to go through a pre-determined pathway amongst the five general IBL phases. Instead, the IBL progress could be nonlinear: students could move back and forth amongst the different IBL phases. The combination of collaborative learning and IBL may facilitate students' learning processes when they externalise their understanding and jointly negotiate how to proceed in the different IBL phases (Bell et al., 2010; de Jong, 2019; Gijlers et al., 2009; Gijlers & de Jong, 2013). Thus, collaborative IBL can be beneficial not only for learning science but also for the skills to do science because researching is nowadays a joint endeavour (Bell et al., 2010; Jensen & Lawson, 2011; Lin et al., 2018). Collaborative IBL can be conducted in non-computerised settings (Kaartinen & Kumpulainen, 2002), but technological resources and particular technological learning environments may support collaborative IBL from the orientation to the conclusion and discussion phases (Bell et al., 2010; de Jong et al., 2018).

In the context of CSCIL, Co-Lab (van Joolingen et al., 2005) and web-based inquiry science environment (WISE) (Slotta, 2004) are widely used research-based environments. Such environments can structure and support groups' CSCIL by facilitating both collaboration and inquiry in the different IBL phases. For example, in the orientation phase, environments may introduce the topic of inquiry that may activate students' prior knowledge (van Riesen et al., 2018). In the conceptualisation phase, environments may include hypothesis scratchpads that facilitate the formulation of testable hypotheses (van Joolingen et al., 2005). In the investigation phase, environments may include technological resources for data collection, analysis and reporting. Moreover, applying technological resources, such as simulations, is typical when students discover phenomena themselves. In the conclusion phase, environments may make visible the ideas from different sources that can support students in jointly building explanations. In the discussion phase, environments can emphasise and foster 'reflection-in-action:' Co-Lab, for example, is based on synchronous online interaction so that students can see and contribute to the inquiry actions of each other and discuss them using the chat function (van Joolingen et al., 2005). Idea Manager is an example tool of WISE that can be used for sharing own ideas and selecting ideas from peers to develop scientifically justified conceptions (Linn et al., 2003; Matuk & Linn, 2018).

In sum, I define CSCIL as a technologically supported, facilitated and mediated negotiation process amongst individuals (Tan, 2018), in which the students follow the practices of scientists to solve problems (Pedaste et al., 2015). This definition of CSCIL is aligned with the work of scientists who collaborate in technology-enhanced research settings. Researchers have been studying CSCIL since many years (e.g. Lipponen & Hakkarainen, 1997; Suthers et al., 1997); therefore, many benefits and challenges regarding CSCIL have been identified. Instead of remembering individual facts, learning to apply scientific concepts and methods with the help of technological resources (such as numerical problem-solving tools; see sub-studies III and IV) is an achievable learning outcome. As a challenge of CSCIL, Arnold et al. (2014) noted that students need assistance both for procedural knowledge (what and how to do) and for procedural understanding (why to do). For example, how and why to use novel technologies (such as the numerical problem-solving tools) in inquiry might not be obvious to students. Alfieri et al. (2011) stated that the benefits of IBL are achieved only when IBL is assisted. Although collaboration and computer-support can assist IBL (Bell et al., 2010; Gijlers et al., 2009; Wang et al., 2014), recent studies indicate that additional guidance can further enhance IBL in CSCL settings (e.g. Ibáñez & Delgado-Kloos, 2018; Rau et al., 2017; see also sub-study III). When de Jong and Lazonder (2014) provided the typology of guidance, which can be used to enhance IBL (see Lazonder & Harmsen, 2016), the scaffold was defined as a type of guidance with high specificity. In particular, the 'scaffolds often provide students with the components of the process and thus structure the process' (de Jong & Lazonder, 2014, p. 377).

2.1.2 Scaffolding computer-supported collaborative inquiry-based learning

In this study, scaffold means assistance provided to solve the problems that are challenging to complete with students' own effort (Wood et al., 1976). This idea of scaffolding is close to the concept of the zone of proximal development (Vygotsky, 1978) because the scaffolds aim to help students to perform more complex tasks than they could without the scaffolds 'in a way such that they can still learn from that experience' (Quintana et al., 2004, p. 340). Kim and Hannafin (2011) characterised the scaffold by its purposes, interactions and source. In this study, the purpose of the scaffolds is mainly procedural: they help students in negotiating, managing and implementing tasks related to the different IBL phases (cf. de Jong & Lazonder, 2014). The interaction of the scaffolds is static, which means that the scaffolds include fixed and not adaptive guidelines for the students. Whereas Wood et al. (1976) talked about a tutor (meaning, e.g. a teacher or more capable peer) and learner in the singular form when referring to scaffolding problem-solving (i.e. one-to-one interaction), in this study, the source of the scaffold is a technological learning environment, and peers can help in interpreting and adjusting the scaffold to the needs of the group. Quintana et al. (2004) provided a scaffolding design framework for inquiry when the source of the scaffold is a technology. The framework includes science inquiry components, scaffolding guidelines and scaffolding strategies.

In this framework., the science inquiry components include sense-making, process management and articulation and reflection. Regarding sense-making, for example, a scaffolding guideline would be to use different representations that learners can inspect to reveal the important properties of the underlying data. This use of representations can be implemented by enabling learners to inspect multiple views of the same object or data (a scaffolding strategy). Regarding process management (cf. the procedural purpose of the scaffold by Kim & Hannafin, 2011), an example of a scaffolding guideline would be to provide a structure for complex tasks and functionality. This structure can be provided by describing complex tasks using ordered and unordered task decompositions (a scaffolding strategy); for example, the task decomposition can be based on the different IBL phases. Regarding articulation and reflection, the scaffolding guideline stresses the facilitation of ongoing reflection during the inquiry. This facilitation can be enhanced by providing reminders and assistance to promote productive planning (a scaffolding strategy).

Overall, by scaffolding IBL in CSCL settings, I aimed to make students aware of the (technological) resources, tasks and need to externalise their understanding that they might not be fully aware of without scaffolds (Reiser & Tabak, 2014). An example of the scaffolding of IBL in CSCL settings is writing scaffolds. Writing scaffolds can provide procedural assistance to students by instructing them to write down how they conduct different tasks of an inquiry problem; writing can also externalise students' understanding (Gijlers et al., 2009; Hmelo-Silver et al., 2007; Sharma & Hannafin, 2007; see details in sub-study IV). Another example is collaboration scripts (Kollar et al., 2007; Mäkitalo-Siegl et al., 2011; Raes et al., 2012) that I also consider as scaffolds in this study. The scripts have been seen as scaffolds that may facilitate both domain learning and collaboration skills (Radkowitsch et al., 2020; Vogel et al., 2017). In CSCIL contexts, the scripts can describe the activities based on the tasks of the inquiry problem and each student can be given a role based on these activities (Kobbe et al., 2007; see details in sub-study IV).

Regarding the effect of different scaffolds (or more generally, the different types of guidance; de Jong & Lazonder, 2014), no unambiguous differences in their effect of promoting learning outcomes have been found when comparing them with the non-scaffolded condition (Belland et al., 2017a; Lazonder & Harmsen, 2016). Belland et al. (2017b), in addition, analysed within-subject differences resulting from scaffolding and surprisingly found that scaffolding did not affect learning outcomes when IBL was used as a pedagogical approach (owing to the small number of included studies; however, the 95% Bayesian confidence interval for the effect size was wide). Despite the apparent need to study the effect of scaffolds on learning outcomes and other variables, these studies have not necessarily addressed *how* learning occurs and *how* differences emerge amongst the different conditions; addressing these questions could provide input for refining and re-implementing the scaffolds to further enhance students' learning (Alfieri et al., 2011; Kim & Hannafin, 2011; Stahl, 2017). This notion also more generally relates to the challenges of the prevalent lines of CSCL research (Reimann, 2009; Stahl, 2017), which I elaborate on next.

2.2 Prevalent lines of CSCL research

Research on CSCL has a long history. The first line of CSCL research has focused on the effects of collaboration in computer-supported settings (Chen et al., 2018). These studies have compared the effects of some form of collaborative learning with those of individual learning. An example of this line of research is the work of Rebetez et al. (2010), who studied how learning from animated graphics differs between individual and collaborative learning settings when studying astronomy at the university level. They reported the benefits of collaborative learning under certain conditions, even though collaborative learning might be less efficient than individual learning (i.e. a group spends more time performing tasks than an individual).

The second line of research has focused on the effects of using technologies in collaborative learning (Chen et al., 2018). These studies have compared the effects of CSCL with collaborative learning without any technological resources. For example, Rau et al. (2017) recently found that a CSCL intervention led to higher learning gains than collaborative learning did with traditional worksheets in an undergraduate chemistry course. Although the benefits of collaborative learning and computer support depend on the context, currently, a typical premise of CSCL research is that both collaborative learning and technologies support learning when adequately taking the context into account.

The third line of research has focused on the effects of using a specific technology or approach in CSCL (Chen et al., 2018). These studies have compared the effects of the scaffolds or form of communication, for example, on CSCL outcomes and processes. Lin et al. (2018) analysed the effect of an argumentation assistance tool on science process skills and argumentation construction skills when 6th graders solved CSCIL problems. The authors measured these skills by conducting analysis of covariance on the pre- and post-tests. Sins et al. (2011) studied 11th graders when they engaged in a computer-supported inquiry task. They compared two conditions, one that used a synchronous communication technology and the other that was communicated face-to-face. They statistically analysed students' deep- and surface-level reasoning processes in both conditions by comparing the mean percentages of time the groups spent on the different reasoning processes using the Mann–Whitney *U* test. They also analysed students' task performance using the same test. Gijlers and de Jong (2013) analysed the effect of concept maps on consensus-building processes in CSCIL and compared the mean number of utterances in the different modes of knowledge construction by conducting multivariate analysis of covariance.

The common characteristic feature for these three lines of research is that they are built on variables and the analysis of their variance, which Reimann (2009) has called variable-centred analysis. Variable-centred analysis is clearly one of the main methodological paradigms in the current CSCL research (cf. experimental paradigm in Stahl et al., 2014a, p. 493). Jeong et al.'s (2014) study corroborated that inferential statistics and the coding-and-counting approach were the most widely used methods in CSCL research and that these two methods were often adopted together. Considering measurable learning outcomes, attitudes, interest and motivation, for example, variable-centred analysis provides a worthwhile approach to study the effect sizes of an intervention and to compare different conditions based on well-established statistical inference practices. Thus, variable-centred analysis mainly focuses on '*what* learning occurs', but CSCL research aims to address '*how* and *why* learning occurs' as well (Ludvigsen & Steier, 2019, p. 3).

Although the chosen examples of variable-centred analysis show that researchers have captured CSCL processes using variables and have aimed to address the *how* question, a misleading assumption (see Csanadi et al., 2018; Swiecki et al., 2020) about both long- and short-term temporal homogeneity (Kapur et al., 2008) has been made. Regarding long-term temporal homogeneity, the effects of independent or explanatory variables (e.g. the coded units of analysis) on the dependent variable are assumed to be constant in a long temporal context (Chiu & Khoo, 2005; Reimann, 2009). This long temporal context may include the entire CSCL session or a sequence of sessions; thus, the frequencies of the coded units of analysis or time spent on specific learning activities are aggregated over these sessions. Regarding short-term temporal homogeneity, the coded units of analysis are interpreted as being isolated from a short temporal context. This short temporal context may include the previous and following units of analysis. Because CSCL – and learning, in general – is a process that unfolds over time, the minor role of time in research (Barbera et al., 2015) seems surprising.

To better address the *how* question, CSCL research could consider how learning as a process unfolds over time (Stahl, 2017). Because students' ways of using technologies and realisations of new learning approaches can differ from their actual design (Wang & Hannafin, 2005), research taking the time variable into account could provide valuable insights into how to 'design, test, and refine' (Stahl, 2017, p. 113) technologies and approaches for CSCL (cf. the third line of research, Chen et al., 2018). Thus, considering time and understanding temporality is seen as necessary in CSCL research (Ludvigsen et al., 2018). The temporal analysis of CSCL forms the basis for the methodological framework of this dissertation (section 3), and the development of the temporal analysis for CSCL is the aim of this dissertation (section 4).

3 METHODOLOGICAL FRAMEWORK

In this section, I present the methodological framework for this dissertation. After briefly introducing the motivation for temporal analysis in CSCL research, I provide an overview of the temporal analysis methods. I conclude this section with the limitations of the temporal analysis of CSCL and the needs to develop further the temporal analysis for CSCL.

3.1 Temporal analysis

To increase the validity of inferences concerning CSCL as a process unfolding over time, approaches that consider the temporal aspects of CSCL are needed. The idea to include time as a variable in learning research is not a new one. For example, Lemke (2000) presented timescales for different processes associated with learning (from chemical synthesis to universal change through neural firings, lessons and semesters, for example) and discussed how lower-level processes are associated with the process of interest, which, in turn, is constrained by higher-level processes. A practical reason for the increasing popularity of studying the temporal aspects of CSCL is the ease of capturing learning process data owing to technological development. A way to study the temporal aspects of CSCL is to consider the events of interest that the process data reveals (Reimann, 2009). In this study, I use the term 'temporal aspects of CSCL' when analysing these events to understand CSCL as a process unfolding over time. I broadly define the temporal aspects of CSCL as those focusing on the characteristics of the events or the interrelations between these events over time.

The temporal aspects of CSCL can be analysed using novel process data, such as eye-tracking (Schneider & Pea, 2013) or physiological measurements (Haataja et al., 2018). Today, the capacity of computers to analyse complex process data does not restrict the analysis. Moreover, 'traditional' video and audio data and their transcriptions can provide temporal information that can be analysed in various ways (see sub-studies III and IV). For example, these data can address essential questions, such as the following: who is talking to whom (social network analysis; see Dado & Bodemer, 2017), how are the specific sequences of cognitions over time related to learning outcomes (statistical discourse analysis; Molenaar & Chiu, 2017), how is the participation equity of different students evolving (visualisations; Kapur et al., 2008) or how are the technological and social resources of learning intertwined (qualitative analysis such as conversation analysis; Oner, 2013)?

Temporality has been considered in two different ways in the learning sciences (Knight et al., 2017). First, research has focused on the characteristics of or the interrelations between events over time in a long temporal context (e.g. the entire CSCL session or a sequence of sessions; see sub-study I). This explicit monitoring of time (Knight et al., 2017) can reveal the intertwining aspects of CSCL (see Järvelä et al., 2019; Malmberg et al., 2019; Medina & Suthers, 2013), such as the role that students' ways of using technological resources play when they jointly develop ideas and thoughts. Second, research has focused on the characteristics of or the interrelations between events over time in a short temporal context (e.g. a few consecutive utterances; see sub-study I). These sequences of two or a few events, for example, are interpreted without information about their temporal emergence, duration or development over time (Knight et al., 2017). A key assumption is that every event receives input from the previous events and provides output to the following events. These different considerations about temporality are also visible in the temporal analysis methods that have been used in CSCL research.

3.2 Temporal analysis methods

Over the last ten years, the CSCL community has implemented various novel temporal analysis methods to better understand how CSCL as a process unfolds over time (Dado & Bodemer, 2017; sub-study I). These methods can be classified based on their assumptions about temporality. First, the methods may focus on the explicit monitoring of the characteristics of or the interrelations between events over time (Knight et al., 2017). As an example, I visualised different temporal aspects of CSCIL based on video and audio data (see sub-study III and section 6.1.5). Although the explicit monitoring of time through visualisations or other qualitative techniques may be criticised for only analysing some examples in-depth without generalisability, these studies are needed to understand which temporal aspects deserve further investigations. I also showed how visualisations can be interpreted with the help of statistical testing: I visualised 46 groups' use of technological resources in CSCIL based on log data and conducted TLDA (see sub-study IV and section 6.2.5).

Second, the methods may focus on the characteristics of or the interrelations between events over time within two or a few consecutive or co-occurring events, for example. Frequently adopted temporal analysis methods in CSCL research, such as lag sequential analysis (LSA) (see sub-study IV and section 6.2.5) and social network analysis, typically reveal the sequences of a few consecutive events. These two assumptions about temporality are not necessarily exclusionary. For example, I advanced LSA and developed TLSA that determines both the statistically significant two-event sequences (based on LSA; short temporal context) and monitors the averaged time instants when the sequences emerge (long temporal context; see sub-study IV and section 6.2.5). Another example is process mining that assumes processes to be sequential so that the latent process governs these sequences in the background (Bannert et al., 2014). As a result, the processes are illustrated as a chain of sequences from the beginning to the end of CSCL. I elaborate on the temporal analysis methods and their distinctions in sub-study I.

The findings based on temporal analysis can provide new insights both for the teachers and developers of educational technologies. From the teachers' viewpoint, knowledge about CSCL as a process unfolding over time can be used for refining learning activities (e.g. Lin et al., 2013), for further developing instructional practices (e.g. Hou & Wu, 2011), for monitoring students' learning processes in real time (e.g. Su et al., 2018) and for scaffolding learning (e.g. Wu et al., 2013). From the viewpoint of the developers of educational technologies, these findings can be used for designing, implementing, testing and refining tools and functionalities for technological learning environments (e.g. Eryilmaz et al., 2013). Despite the many advantages and even the hype of temporal analysis, emerging and data-intensive analysis techniques have also given rise to doubts (Wise & Schwarz, 2017).

3.3 Limitations of temporal analysis

Contrary to the well-established, variable-based statistical inference practices (section 2.2), there are no established practices for analysing the temporal aspects of CSCL or learning in general (e.g. Mercer, 2008). Because of the different conventions and methods to refer to the temporal analysis of CSCL (sections 3.1 and 3.2), Knight et al. (2017) called for researchers to conceptualise the temporal nature of learning construct, to capture and analyse the learning process data according to the conceptualisations and to utilise methods that reveal the temporal aspects of interest from the data. Molenaar (2014) called for guidelines for the different steps of temporal analysis to move this line of research forward. Thus, the first limitation of temporal analysis is theoretical and relates to the lack of established practices for the analysis of the temporal aspects of CSCL. This makes it challenging to choose what process data to collect and what methods to adopt to address the research aims regarding the temporal aspects of CSCL. Consequently, this may lead to collecting process data and adopting methods that are inappropriate from the viewpoint of the theoretical framework and aims of the study. Such inappropriate choices make studies incommensurable and incomparable. Despite the lack of established practices for analysing the temporal aspects of CSCL, researchers have increasingly published studies applying temporal analysis to CSCL (sub-study I). These studies, however, have so far proceeded with a quite narrow focus (Dado & Bodemer, 2017; sub-study I).

The second limitation of the temporal analysis of CSCL relates to the lack of studies that explicitly monitor the characteristics of or the interrelations between events over time (see sections 3.1 and 3.2). Instead, the current studies and the methods used have mostly relied on mere sequences of two or a few events (Dado & Bodemer, 2017; sub-study I). Although these studies provide valuable insights on productive learning sequences, individual sequences can be problematic to interpret (Csanadi et al., 2018). Advancing and employing methods that allow for the monitoring of the temporal emergence of the sequences could show what sequences are clustered together, which would make finding broader phases of learning processes easier. The information about the time instants of the sequences can also reveal the progress of learning. Moreover, the explicit monitoring of time functions as a methodological tool to capture the temporally intertwining aspects of learning (Oner, 2013). Focusing on these intertwining aspects can lead to a better understanding of CSCL and the premises for productive CSCL (see Ludvigsen & Steier, 2019).

The third limitation of the temporal analysis of CSCL results from the lack of studies focusing on the temporal aspects of IBL in CSCL settings (some exceptions are Chiang et al., 2014; Wang et al., 2014). This seems surprising, given the popularity of CSCL in science education and IBL as a pedagogical approach in CSCL settings (see section 2.1.1; Jeong et al., 2019). In particular, temporal analysis can provide insights for the scaffolding of CSCIL (see Gijlers et al., 2009) when more is known about *how* CSCIL occurs and *how* differences emerge between scaffolded and non-scaffolded CSCIL. This information can help in designing, testing, refining and re-implementing scaffolds to enhance CSCIL. Temporal analysis can specifically illuminate how the designed CSCIL processes differ from the realisations of the CSCIL processes.

To address these three limitations, in the following section, I propose the theoretical, methodological and empirical aims of this study.

4 AIMS OF THE STUDY

The aim of this dissertation is to develop the temporal analysis for CSCL in the context of scaffolded inquiry. In the following sections, I address the study's theoretical, methodological and empirical aims in detail.

4.1 Theoretical aim

To move forward the research on the temporal aspects of CSCL, my theoretical aim is to *develop a temporal analysis procedure for CSCL* (sub-study I). The procedure includes the key operations for analysing the temporal aspects of CSCL; employing this procedure may increase the comparability and commensurability of future studies. In section 5, I present the methods and outcomes when addressing this theoretical aim.

4.2 Methodological and empirical aims

I adapted the temporal analysis procedure (sub-study I and section 4.1) to study the practice phase of the primetime learning model (sub-study II) in undergraduate physics courses. In science education, IBL is a popular pedagogical approach in CSCL settings (Jeong et al., 2019). CSCIL is a process in which different aspects temporally intertwine. To better understand the premises for productive CSCIL (see Ludvigsen & Steier, 2019), my methodological aim is to *advance temporal analysis methods to study CSCIL* (sub-studies III and IV). Researchers widely agree that scaffolding is needed to achieve the benefits of CSCIL; therefore, my empirical aim is to *design scaffolds and analyse their role in CSCIL* (sub-studies III and IV).

To address the empirical aim, I employed the temporal analysis procedure and advanced methods. First, to design scaffolds for CSCIL, I studied *how* CSCIL occurs (sub-study III and section 6.1). Second, to analyse the role of the designed scaffolds in CSCIL, I investigated *how* differences emerge between scaffolded and non-scaffolded conditions (sub-study IV and section 6.2). I have structured sections 6.1 and 6.2 based on the key operations for analysing the temporal aspects of CSCL (sub-study I). In section 6.1.1, I present the sub-aims to address *how* CSCIL occurs. In section 6.2.1, I present the sub-aims to address *how* differences emerge between scaffolded and non-scaffolded CSCIL.

5 TEMPORAL ANALYSIS PROCEDURE FOR CSCL

To address the theoretical aim of the study (to develop a temporal analysis procedure for CSCL; see section 4.1), I conducted a systematic literature review. The literature search included the identification, screening, eligibility and included phases (see Shamseer et al., 2015). These different phases are shown in FIGURE 1 (see the details in sub-study I). Overall, 78 peer-reviewed articles published in high-impact journals (e.g. *Computers & Education*, *n* = 11; *Computers in Human Behavior*, *n* = 5; *International Journal of Computer-Supported Collaborative Learning*, *n* = 11; *Journal of Computer Assisted Learning*, *n* = 4) were included for further analysis.

I identified the six key operations for analysing the temporal aspects of CSCL based on the systematic literature review (FIGURE 2). These key operations are dependent; therefore, the implementation of a key operation is constrained by previous key operations and will constrain the implementation of the following key operations. For example, in face-to-face interaction (context), information about the sequences of events (outcomes) may not be sufficient because the same sequences may have different consequences in the different phases of learning processes; thus, the process data, events and temporal analysis method should be chosen to ensure that the key operations related to the context and outcomes are aligned. In the following sections, I individually present each key operation and elaborate on how the operations were performed in the included 78 papers.

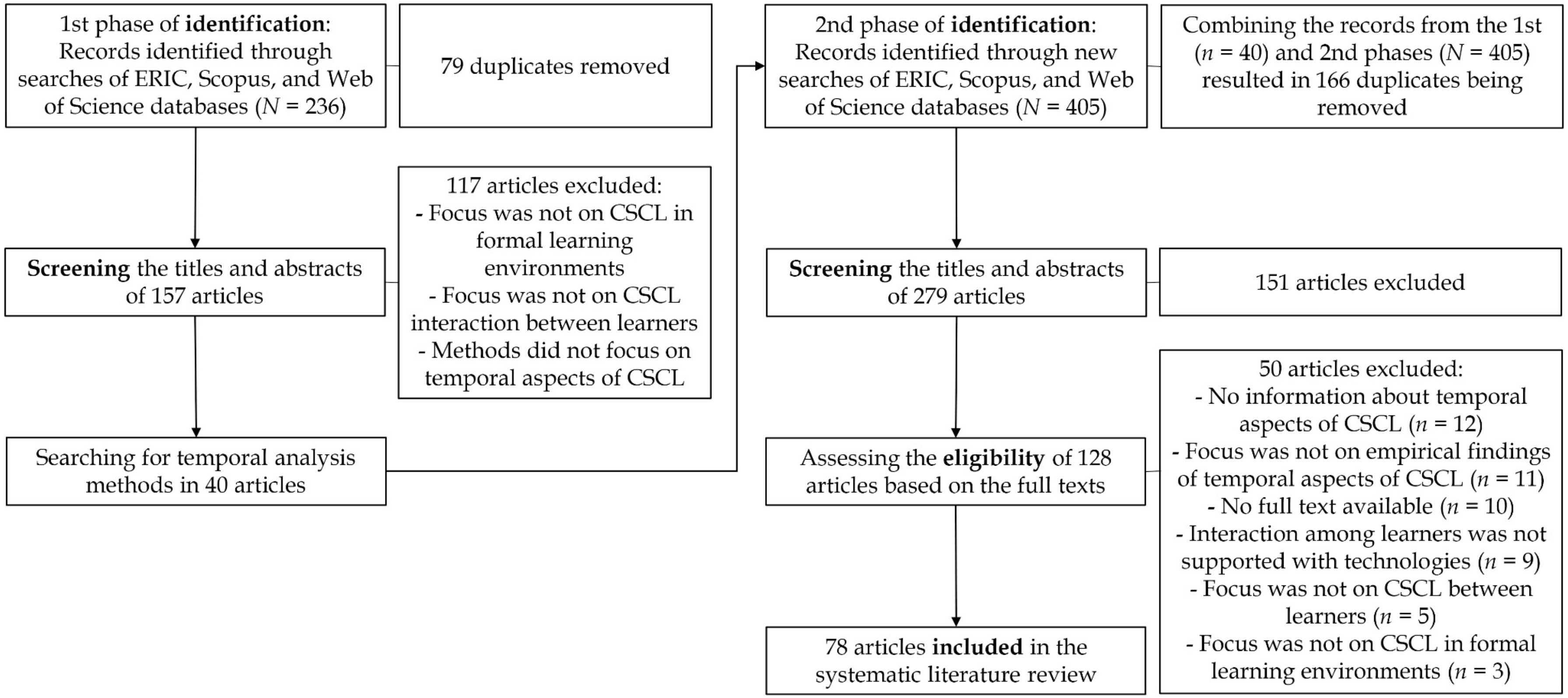

FIGURE 1 The literature search to develop a temporal analysis procedure for CSCL

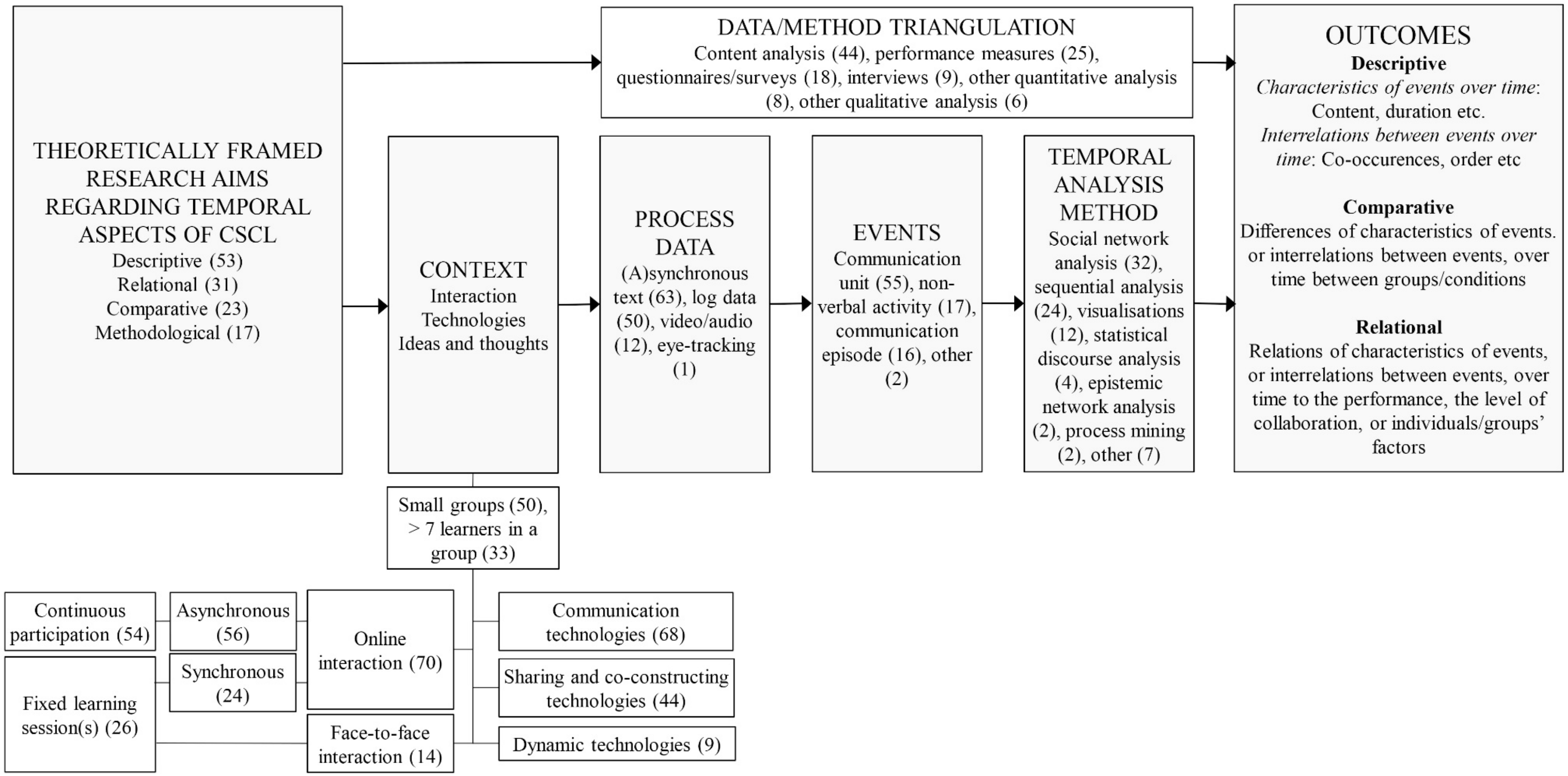

FIGURE 2 The key operations for the analysis of the temporal aspects of CSCL. The key operations are highlighted in grey. The numbers in parentheses refer to the number of articles

5.1 Theoretically framed research aims regarding temporal aspects

The first key operation is to specify the temporal aspects of CSCL that are studied to address the theoretically framed research aims. The systematic literature review showed that, most typically, the studies had descriptive aims (68% of the articles), whereas the relational (40%), comparative (29%) and methodological (22%) aims were rarer. Although the temporal analysis of CSCL was scattered across different theoretical approaches, theoretical frameworks such as knowledge building, regulation of learning and cognitions were widely used.

5.2 Context

The second key operation is to form a context for the study. The context concerns the interaction amongst the students (e.g. whether the interaction is face-to-face or online), technologies used to mediate the interaction (e.g. communication or dynamic technologies) and what ideas and thoughts the students are working on. The systematic literature review showed that interaction was mainly computer-mediated (90%) and therefore communication technologies (87%) (e.g. discussions forums) were used.

5.3 Process data

The third key operation is to decide what process data are to be collected. Owing to the popularity of computer-mediated interaction, 81% of the studies used online discussion as a process data source when conducting temporal analysis; moreover, 23% of the studies had online discussions as the only process data source. In addition, log data (64%) and video/audio data (15%) were used to capture CSCL as a process.

5.4 Events

The fourth key operation is to conceptualise the events from the collected process data. From online discussions or transcriptions of video/audio data, events were typically conceptualised as communication units (71%, e.g. a message) or episodes (21%, e.g. a thread of messages). From log data, a non-verbal activity related to the use of technologies was a typical event (22%).

5.5 Temporal analysis methods

The fifth key operation is to analyse the events by employing one or more temporal analysis methods. The choice of the method depends on the type and number of events and the temporal aspects of CSCL of interest (e.g. whether sequences or co-occurrences of events over time and whether content or duration of events over time). Social network analysis (41%) and sequential analysis (31%) were the most frequently employed methods; thus, the focus was on the sequences of events. Other temporal analysis methods included visualisations[1] (15%), statistical discourse analysis (5%), epistemic network analysis and other network analysis techniques (3%) and process mining (3%).

5.6 Outcomes

The sixth key operation is to interpret the outcomes based on the chosen temporal analysis methods. Depending on the previous key operations, the outcomes related to the temporal aspects of CSCL focused on the characteristics of or interrelations between events over time (descriptive aims); differences of characteristics of, or interrelations between, events over time between groups/conditions (comparative aims); or relationships of characteristics of or interrelations between events over time to the performance, the level of collaboration or individuals'/groups' factors (relational aims). In the reviewed papers, the events were related to learner interaction (e.g. who is talking), the ideas and thoughts developed in the interaction (e.g. what is talked about) and the use of technological resources to mediate the interaction (e.g. what non-verbal activities are conducted). The outcomes were typically sequences of two events related to learner interaction or ideas and thoughts developed in the interaction. Moreover, data and method triangulation complemented the interpretations, which were made by conducting the temporal analysis of CSCL.

In sum, the proposed key operations and their implementations provide a roadmap for this study and other studies focusing on the temporal aspects of CSCL. This roadmap can contribute to establishing practices for the temporal analysis of CSCL that may increase the comparability and commensurability of future studies. Addressing the question of '*how* learning occurs' by conducting temporal analysis also helps to better understand the premises of productive CSCL. In the following section, I show how I implemented the key operations to study the temporal aspects of CSCL in the context of scaffolded IBL.

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[1] In this study, I refer to visualisations as a method in its own right. Visualisations of outcomes are frequently used in conjunction with other listed temporal analysis methods, but those are not counted to this frequency.

6 TEMPORAL ANALYSIS OF COMPUTER-SUPPORTED COLLABORATIVE INQUIRY-BASED LEARNING

To address the methodological and empirical aims of this study (section 4.2, to advance temporal analysis methods to study CSCIL; to design scaffolds and analyse their role in CSCIL), I applied the six key operations (sections 5.1–5.6; see also sub-study I) to study the temporal aspects of CSCIL. I addressed the empirical aim by developing the practice phase of the primetime learning model (sub-study II) in undergraduate thermodynamics courses at the University of Jyväskylä (sub-studies III and IV). As part of the primetime learning model, the students were divided into groups of five (a few groups included four or six students), which were heterogeneous regarding gender, major and performance. In the practice phase, the groups collaboratively solved problems face-to-face in a technological learning environment with a shared laptop computer and without a teacher. An essential part of the practice phase was to learn to use different technological resources (e.g. dynamic technologies such as the Python program) when solving inquiry problems. The technological learning environment used in this study was The Interactive Material (TIM) (https://tim.jyu.fi) because it enabled us to implement all the material and resources needed in the courses at the same place. The participants of sub-study III comprised ten undergraduate natural science students (two groups). The participants of sub-study IV comprised 231 undergraduate natural science students (46 groups).

In this study, the temporal aspects of CSCIL of interest were (i) sequences of events over time, wherein the events were related to students' ideas and thoughts characterised by the different IBL phases and (ii) characteristics of events over time, wherein the events were related to the students' ways of using technological resources. First, focusing on the sequences is a way to examine IBL in CSCL settings: the sequential nature of IBL is also visible in the framework developed by Pedaste et al. (2015), wherein students can move back and forth between the different IBL phases without pre-determined pathways. Second, despite the importance of technological resources in CSCL, their intertwining role in learning activities has often been neglected (Bernhard, 2018; Chen et al., 2019; Ludvigsen & Steier, 2019). Focusing on this interplay can help to identify the critical design principles of the educational technologies. Thus, I studied how IBL sequences temporally intertwine with the students' ways of using technological resources.

I have divided the rest of this section based on the six key operations of temporal analysis (sections 5.1–5.6). I present the implementations of these operations from the viewpoint of sub-studies III (designing scaffolds for CSCIL by studying *how* CSCIL occurs, section 6.1) and IV (analysing the role of the designed scaffolds in CSCIL by studying *how* differences emerge between the scaffolded and non-scaffolded conditions, section 6.2). I present the summary of sub-studies I, III and IV in TABLE 1. TABLE 1 shows the relations between the aims of this dissertation (section 4) and the sub-studies.

6.1 Designing scaffolds

In this section, I study *how* CSCIL occurs to design scaffolds for CSCIL. The analysis is based on the temporal aspects of CSCIL, which focus on the IBL sequences over time and the intertwining role of the use of the Python program in these sequences over time. Next, I elaborate on how I implemented the key operations of the temporal analysis in sub-study III (see FIGURE 2 and TABLE 1).

6.1.1 Research aim: How does computer-supported collaborative inquiry-based learning occur?

To study *how* CSCIL occurs, I addressed the following methodological and descriptive sub-aims. My methodological sub-aim was to develop visualisations of CSCIL that capture its temporally intertwining aspects. My descriptive sub-aims regarding the temporal aspects of CSCIL were to investigate the following:

1. the progress of CSCIL by visualising the CSCIL processes over time and identifying the characteristic IBL sequences; and
2. the intertwining role of the Python program in the characteristic IBL sequences by visualising whether the use of the Python program occurred at a deep level or surface level or whether it was non-existent.

TABLE 1 Implementations of the key operations of temporal analysis (sub-study I) when analysing computer-supported collaborative inquiry-based learning in sub-studies III and IV

	Sub-aims	**Context**	**Process data**	**Events**	**Temporal analysis method**	**Outcomes**
Sub-study III: How CSCIL occurs	Methodological: Advance the visualisations of CSCIL Descriptive: Identify the characteristic IBL sequences and the intertwining role of the Python program in these sequences over time	Face-to-face interaction Dynamic technologies (Python program) Ideas and thoughts about the random walk problem in undergraduate thermodynamics courses	Screen-capture videos and audio recordings of two groups (n = 10)	Communication episodes – that is, a few utterances (the IBL phase) Communication units – that is, utterance (the use of the Python program)	Visualisations	Descriptive: Both challenges and productive practices, which occurred when the Python program was used, were temporally intertwined with specific IBL sequences
Sub-study IV: How differences emerge between the scaffolded and non-scaffolded conditions	Methodological: Advance TLDA and TLSA Comparative: Compare the IBL sequences and the intertwining role of the Python program in these sequences over time	Face-to-face interaction Dynamic technologies (Python program) Ideas and thoughts about the random walk problem in undergraduate thermodynamics courses	Screen-capture videos and audio recordings of 11 groups (n = 55) Log data from 46 groups (N = 231)	Communication episodes (the IBL phase) Non-verbal activities showing the runs with the Python program with timestamps (the use of the Python program)	TLSA TLDA	Comparative: Three temporally distinct IBL sequence clusters (orientation–investigation–conclusion/discussion) were found in both the scaffolded and non-scaffolded conditions. The temporally different ways of using the Python program were associated with the differences in the content and temporal emergence of the clusters between the scaffolded and non-scaffolded conditions

6.1.2 Context: Face-to-face interaction mediated by a dynamic technology

My analysis focused on two groups' CSCIL processes (Groups 1 and 2) in the practice phase of the primetime learning model, wherein the groups solved a random walk problem (FIGURE 3) in a fixed learning session. The duration of the sessions was 22 and 18 min in Groups 1 and 2, respectively. Group 1 correctly solved the problem, whereas Group 2 did not reach the correct solution. The groups interacted face-to-face using a shared laptop computer and used a Python program as a dynamic technology to solve the problem. The groups' aim was to determine how the displacement of an atom in a two-dimensional gas depends on time [FIGURE 3 (a)]. The solution of the random walk problem required that the groups (i) run the Python program with different values of the number of collisions of the atom and (ii) run the Python program multiple times with the same value of the number of collisions to infer the time-dependence of the averaged value of the displacement [FIGURE 3 (b) and (c)]. The groups also had access to a YouTube video clip that provided a representation of the random walk [FIGURE 3 (d)].

6.1.3 Process data: Screen-capture videos and audio recordings

I analysed the CSCIL processes of two groups using screen-capture videos of the groups' computer screen and audio recordings of the conversations. I transcribed the groups' communication based on the video and audio data.

6.1.4 Events: Communication episodes and units

I conceptualised two types of events from the transcriptions. To study the progress of CSCIL (the first descriptive sub-aim, section 6.1.1), I conceptualised communication episodes with the start and end times of the episodes. A communication episode included a few utterances and captured a 'unit of meaning' from the transcriptions (Henri, 1992, p. 134). I coded the communication episodes to the different IBL phases (orientation, conceptualisation, investigation, conclusion and discussion), which I have described in section 2.1.1.

To study the role of the Python program in CSCIL (the second descriptive sub-aim, section 6.1.1), I conceptualised the communication units. A communication unit was an utterance in the transcriptions. I coded the communication units based on the use of the Python program (deep-level use, surface-level use or non-existent), as shown in TABLE 2.

(a)

Assignment 6

The movement of an atom in a gas resembles random walk. Watch first a related video, below:

- Random walk and Maxwell-Boltzmann -distribution

Let us assume that after each collision atom moves exactly the free mean path λ in random direction. (This is not particularly realistic assumption, as you may see from the video.) During the time t atom has collided $N = \frac{t}{\lambda/v_{avg}}$ times, so the atom's total displacement vector is the sum of displacements, $\mathbf{r}(t) = \sum_{i=1}^{N} \mathbf{\Delta r}_i$ (when $\mathbf{r}(0) = 0$).

Calculate how the magnitude of the total displacement $d(t) = |\mathbf{r}(t)|$ depends on the number of collisions N (or on time t, since $t \propto N$). (*Hint: note that* $d(t) = |\mathbf{r}(t)| = \sqrt{\mathbf{r}(t) \cdot \mathbf{r}(t)}$, *with displacements in random directions.*)

Use the script below to verify your calculations (by changing the magnitude of N with $N \lesssim 1000$). In the end, answer the question.

How does the total displacement depend on time?

- $d(t) \propto t$
- $d(t) \propto \sqrt{t}$
- $d(t) \propto t^2$

(b)

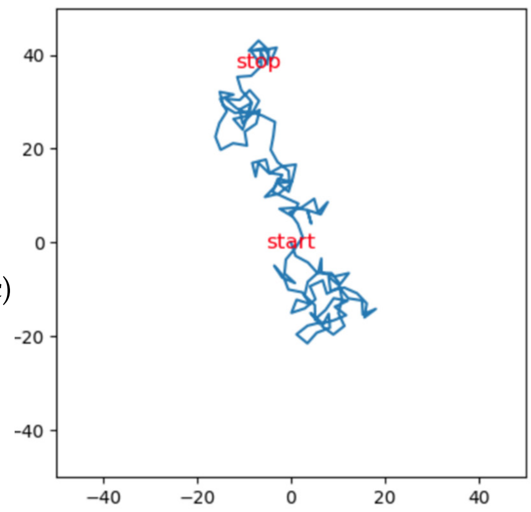
Diffusion in a plane

```
l = 1.        # mean free path
N = 500       # number of collisions
x,y = 0., 0.
r = zeros((N,2))
r[0,:] = [0,0]                # diffusion starts from the origin
for i in range(1,N):
    next_fly = l              # more realistically the path changes:: next_fly=expon
    angle = 2*pi*random()     # direction is randomized
    x += next_fly*cos(angle)  # let's make the displacement
    y += next_fly*sin(angle)
    r[i,0] = x                # update position vector
    r[i,1] = y
length = sqrt(r[-1,0]**2+r[-1,1]**2) # displacement after N collisions
print('path length',length)

axes(aspect='equal')
plot(r[:,0],r[:,1])
```

Run script

(c)



path length 39.0900883545

(d)

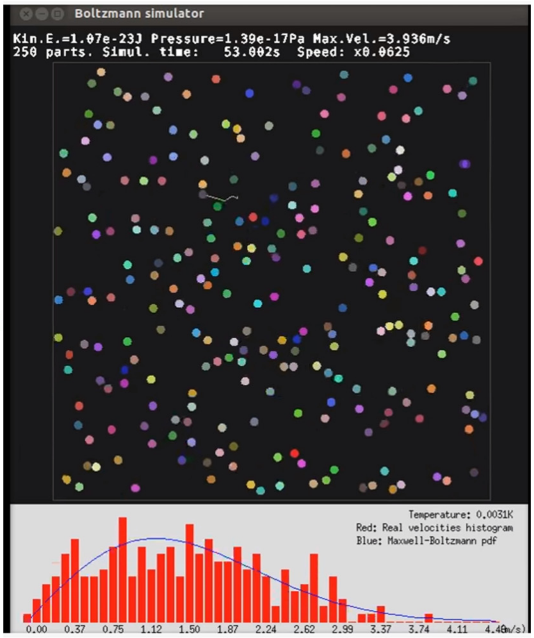


FIGURE 3 The random walk problem: (a) the assignment, (b) Python program used to solve the problem, (c) output of the Python program, including the atom's path and value of the displacement and (d) YouTube video clip, which provided a representation of the random walk

TABLE 2 The codes of the events related to the use of the Python program

Class	Description	Example
Surface-level use of technology	Students used the Python program for routine manipulations and information collection. This typically included running the Python program and collecting or observing the data given by the Python program.	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 it with N = 500. I'll run this [the Python program] a couple of times: 11, 15, 25, 21, 15… [the values of the displacement].
Deep-level use of technology	Students used the Python program for structuring, analysing and interpreting information. This typically included asking a question about the program, interpreting the program itself, modifying the program, interpreting or explaining the results given by the program and planning the use of the program.	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 time] or linear if you set N = 2000 [in the Python program], for instance.

6.1.5 Temporal analysis methods: Visualisations

Visualisations, as a method in its own right, reveal the flow of events in a timeline and show the characteristic features of the data that would be difficult to capture otherwise (cf. time series analysis that typically starts with visualising the data and finding possible trends or seasonal variations). Visualisations can be considered as 'an intermediate step' (Langley, 1999, p. 702) when phenomena are conceptualised; therefore, they are suitable to address the descriptive sub-aims. To study the progress of CSCIL (the first descriptive sub-aim, section 6.1.1), I visualised the communication episodes over time by the labelling start and end times of each episode. I used the MATLAB software to perform the visualisations. In the visualisations, the transitions from one IBL phase to another (i.e. the IBL sequences) demonstrated the dynamics of the CSCIL processes. The visualisations allowed me to focus on the IBL sequences that characterised the CSCIL processes of the two groups. To study the role of the Python program in CSCIL (the second descriptive sub-aim, section 6.1.1), I visualised the communication units, which indicated the students' way of using the Python program in an utterance over time. I focused on the groups' ways of using the Python program in the characteristic IBL sequences.

6.1.6 Outcomes: Temporal challenges and productive practices guide the design of scaffolds

Regarding the progress of CSCIL (the first descriptive sub-aim, section 6.1.1), I found that instead of the amount of time the groups spent on one specific IBL phase (cf. coding-and-counting method), the between-group differences in the most frequent IBL sequences characterised the groups' CSCIL processes (see FIGURE 4). Group 1 had the most frequent IBL sequence between the investigation and discussion phases (12 times), and they correctly solved the problem. Group 2 had the most frequent IBL sequence between the orientation and investigation phases (six times), and they did not reach the correct solution to the problem.

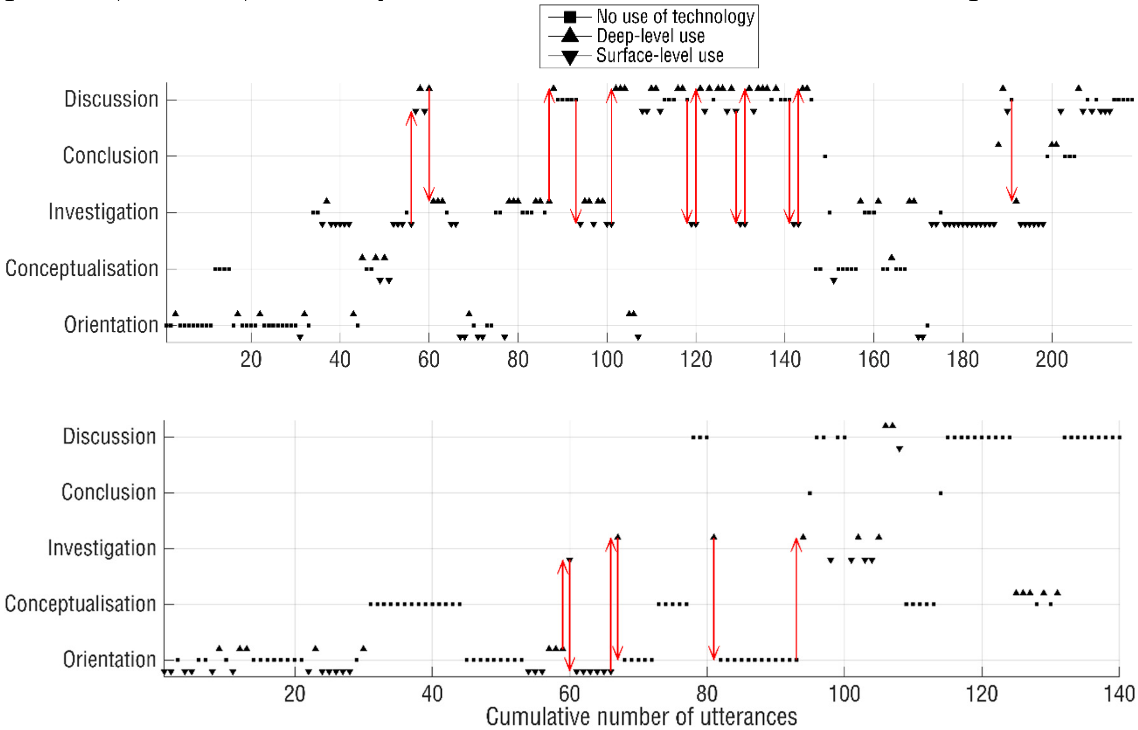


FIGURE 4 Visualisations of the computer-supported collaborative inquiry-based learning processes of Group 1 (top) and Group 2 (bottom) showing the groups' most frequent inquiry-based learning sequences (arrows) and the use of the Python program (symbols) over time

Regarding the role of the Python program in CSCIL (the second descriptive sub-aim, section 6.1.1), I found that the most frequent IBL sequences were triggered by the use of the Python program (FIGURE 4). Group 1 had recurrent, surface-level use of the Python program (e.g. data collection) in the investigation phase, triggering the transitions to the discussion phase, where the use of the Python program occurred on a deep level (e.g. communicating and reflecting on the findings and the current ways of using the Python program). In contrast, Group 2 had recurrent IBL sequences between the orientation and investigation phases. These sequences may be explained by the challenges that Group 2 faced while trying to use the Python program on a surface level in the investigation phase: Group 2 could not implement the planned activities (deep-level use of the Python program) in their practice (surface-level use of the Python program). This group's attempts to use the Python program during the investigation phase ended up in the orientation phase with no use or surface-level use of the Python program. Thus, Group 2 had to answer the question and make conclusions without the data that supported any of the given options.

The visualisations in FIGURE 4 do not reveal the causal relationships between the IBL sequences and the use of the Python program, but they explicitly indicate how the challenges or productive practices that occurred when the groups used the Python program were temporally intertwined with the specific IBL sequences. I used these results to design scaffolds to enhance the productive use of the Python program as part of CSCIL (e.g. to enhance repetitive sequences between the investigation and discussion phases). In particular, the scaffolds implemented in the technological learning environment aimed to provide procedural assistance for CSCIL with hints on how to use the Python program, especially at the beginning of CSCIL (e.g. to avoid repetitive sequences between the orientation and investigation phases). Although the collaboration could have helped students to make their thinking explicit (Järvelä et al., 2008), the externalisation of thinking did not automatically occur (see sub-study III); therefore, the scaffolds also guided the students to this externalisation. TABLE 3 shows the tasks, challenges and content of the scaffolds in the different IBL phases. Note that previous research has identified similar challenges in different contexts (Chang et al., 2017; de Jong & Van Joolingen, 1998; Kapur et al., 2008; Koretsky et al., 2016; Wang et al., 2014).

The first designed scaffold (writing scaffold) instructed students to write down the essential aspects of the orientation, conceptualisation and investigation phases in the technological learning environment; therefore, for each phase, the groups had a separate place where one of the students could write down the group's joint answers. The writing scaffold implicitly played a role in the interaction of the groups because it fostered the externalisation of the students' thinking (cf. Gijlers et al., 2009). The second designed scaffold (script scaffold) instructed the students to adopt roles. Accordingly, each of the five students in a group adopted a role based on an IBL phase (see, collaboration scripts in Kobbe et al., 2007). The contents of the writing and script scaffolds were similar in the orientation, conceptualisation and investigation phases, but the script scaffold also included non-specific guidelines for the conclusion and discussion phases. Moreover, the script scaffold explicitly aimed to structure the interaction and enhance the externalisation of the understanding in the groups, in addition to providing the procedural assistance for CSCIL with hints on how to use the Python program. In the following, I present what kind of role these scaffolds played in CSCIL by describing *how* differences emerged between the scaffolded and non-scaffolded conditions.

TABLE 3 Tasks of the random walk problem in the different inquiry-based learning phases, challenges identified in groups' learning processes and two scaffolds designed to address the challenges

Phase	Tasks	Challenges	Writing scaffold	Script scaffold
Orientation	Identify the main concepts of the assignment (free mean path, path, total displacement) and become familiar with the technological resources (video and Python program).	Become familiar with the technological resources provided.	Write down the key physics concepts of the assignment. Consider how these concepts are represented in the video, Python program and output of the Python program.	For Student 1: Make sure that everyone in the group identifies the key physics concepts of the assignment. Consider how these concepts are represented in the video, Python program and output of the Python program.
Conceptualisation	Determine the dependent variables (total displacement) and independent variables (number of collisions and amount of time).	Identify dependent and independent variables from the assignment and Python program.	Write down how the question (How does the displacement of an atom in a gas depend on time?) relates to the video, Python program and output of the Python program. Reason how you should utilise the Python program so that you are able to answer the question.	For Student 2: Make sure that everyone in the group understands how the question relates to the video, Python program and output of the Python program. Reason how you should utilise the Python program so that you are able to answer the question.
Investigation	Plan the data collection procedure, implement the procedure and analyse and interpret the collected data.	Plan and implement a proper data collection strategy.	Write down the joint strategy you will implement to answer the question.	For Student 3: Make sure that you plan and implement the joint strategy to answer the question.
Conclusion	Offer and evaluate solutions to the given question based on the data.	-	-	For Student 4: Ensure that you make justified conclusions to solve the problem.
Discussion	Elaborate on the findings and conclusions and reflect on the joint CSCIL processes.	-	-	For Student 5: Make sure that you reflect upon your activities throughout the processes.

6.2 Analysing the role of the scaffolds in learning

In this section, I study *how* differences emerge between the scaffolded and non-scaffolded conditions to analyse the role of the writing scaffold and script scaffold (TABLE 3) in CSCIL. Sub-study III showed how the IBL sequences and the use of the Python program temporally intertwined; therefore, I continued examining these temporal aspects of CSCIL. Next, I elaborate on how I implemented the key operations of the temporal analysis in sub-study IV (see FIGURE 2 and TABLE 1).

6.2.1 Research aims: How do differences emerge between the scaffolded and non-scaffolded conditions?

To study *how* differences emerged between the scaffolded and non-scaffolded conditions, I addressed the following methodological and comparative sub-aims. My methodological sub-aim was to develop TLDA and advance LSA by conducting TLSA. By combining TLDA and TLSA, I determined how the log data (the use of the Python program) could be interpreted by complementing it with the screen-capture video and audio data of CSCIL (IBL sequences) in face-to-face interaction. My comparative sub-aims regarding the temporal aspects of CSCIL were to study the following:

1. the use of the Python program in the different conditions and the temporal distinctions amongst the writing scaffolded, script scaffolded and non-scaffolded conditions;
2. the IBL sequences in the different conditions and the temporal distinctions amongst the conditions.

6.2.2 Context: Face-to-face interaction mediated by a dynamic technology

My analysis focused on 46 groups' CSCIL processes when the groups solved a random walk problem (N = 231, FIGURE 3) in a fixed learning session. The context was otherwise similar as described in section 6.1.2, but 17 groups (n = 86) had the writing scaffold, 15 groups (n = 75) had the script scaffold and 14 groups (n = 70) had no scaffold when they solved the random walk problem (see TABLE 3). The duration of the learning session was on average 28 (SD = 12 min), 19 (SD = 9 min) and 19 min (SD = 8 min) in the writing scaffolded, script scaffolded and non-scaffolded conditions, respectively.

6.2.3 Process data: Log data, screen-capture videos and audio recordings

To study the use of the Python program (the first comparative sub-aim, section 6.2.1), I used the log data of all the groups from the technological learning environment. The log data captured the groups' non-verbal activities in the technological learning environment, and the data showed, for example, when the groups ran the Python program and what the values of the variables were in the run [FIGURE 3 (b)].

To study the IBL sequences (the second comparative sub-aim, section 6.2.1), I used screen-capture videos of 11 groups' computer screen and audio recordings of the conversations (three, four and four groups in the writing scaffolded, script scaffolded and non-scaffolded conditions, respectively). I transcribed the groups' communication based on the screen-capture video and audio data (cf. section 6.1.3).

6.2.4 Events: Non-verbal activities related to the use of the dynamic technology and communication episodes

To study the use of the Python program (the first comparative sub-aim, section 6.2.1), I conceptualised an event from the log data as a run with the Python program with a related timestamp. To study the IBL sequences (the second comparative aim, section 6.2.1), I conceptualised an event from the video and audio data as a communication episode with the start and end times of the episode; the communication episode captured a meaningful unity from the students' conversations. I coded the episodes to the different IBL phases (cf. section 6.1.4).

6.2.5 Temporal analysis methods: Temporal log data analysis and temporal lag sequential analysis

To study the use of the Python program (the first comparative sub-aim, section 6.2.1), I conducted TLDA, revealing how the frequency of the events (runs with the Python program) behaved as a function of time. Next, I plotted empirical cumulative distribution functions (ECDFs) in the different conditions. The value of an ECDF (from 0 to 1) indicates the fraction of the total number of runs with the Python program that have been performed before that time instant. I conducted both one-sample and two-sample Kolmogorov–Smirnov tests to measure how these ECDFs fit to the uniform distribution model and if the ECDFs were similar in the different conditions, respectively.

To study the IBL sequences (the second comparative sub-aim, section 6.2.1), I conducted LSA. I calculated Yule's Q (Davis, 1971) for each sequence in the different conditions. For further analysis, I chose the sequences whose Yule's Q > 0.3, which indicated a moderate positive association in the sequence. I conducted TLSA by determining the averaged time instant for the IBL sequences whose Yule's Q >0.3. Both TLDA and TLSA were performed using R software.

6.2.6 Outcomes: The beginning of learning processes may define the role of the scaffolds

Regarding the use of the Python program (the first comparative sub-aim, section 6.2.1), FIGURE 5 shows that the groups in the writing scaffolded condition evenly used the Python program throughout their CSCIL (one-sample Kolmogorov–

Smirnov: $D = 0.069$, $p = 0.26$). The groups in the script scaffolded and non-scaffolded conditions used the Python program less frequently at the beginning of their CSCIL ($D = 0.15$, $p < 0.001$ and $D = 0.20$, $p < 0.001$), but the use of the Python program was temporally similar in these two conditions (two-sample Kolmogorov–Smirnov: $D = 0.095$, $p = 0.45$).

Regarding the IBL sequences (the second comparative sub-aim, section 6.2.1), FIGURE 6 shows three temporally separate IBL sequence clusters in all three conditions. Whereas the groups in the script scaffolded and non-scaffolded conditions had their first IBL sequence cluster (associated with the orientation phase) before they familiarised themselves with the Python program, the groups in the writing scaffolded condition had their first IBL sequence cluster when they were already familiar with the Python program (FIGURE 5 and FIGURE 6). This familiarity with the Python program might have contributed to more diverse IBL sequences in the first cluster of the groups in the writing scaffolded condition. The second IBL sequence cluster, associated with the investigation phase, also emerged later in the groups in the writing scaffolded condition compared with the groups in the script scaffolded and non-scaffolded conditions. The third IBL sequence cluster was associated with the conclusion and discussion phases and emerged at the same time in all three conditions.

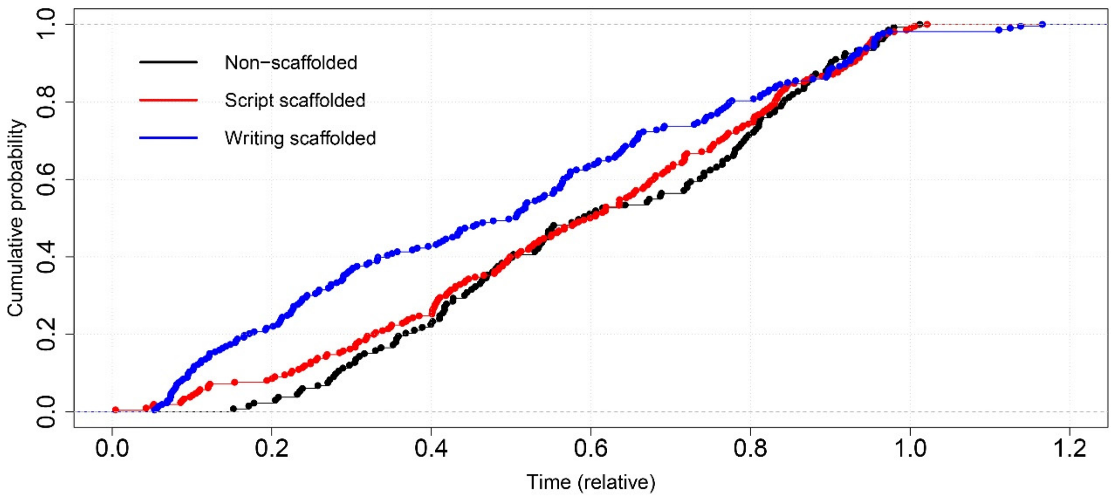


FIGURE 5 The results of temporal log data analysis showing the use of the Python program in the scaffolded and non-scaffolded conditions over time. At any given time instant, the value of the empirical cumulative distribution function was equal to the fraction of the total number of runs with the Python program that had been performed before that time instant. Time = 0 refers to the moment when the solution to the previous problem was submitted. Time = 1 refers to the moment when the solution to the random walk problem was submitted.

Although CSCIL is a complex and non-linear process, the findings of TLSA showed the general progress of CSCIL (FIGURE 6). This general progress was similar in the writing scaffolded, script scaffolded and non-scaffolded conditions, but the actual content and temporal emergence of the IBL sequence clusters varied. FIGURE 5 and FIGURE 6 also show that the role of the writing scaffold was not uniform throughout the CSCIL and was the most significant at the beginning: the groups in the writing scaffolded condition used the Python program more frequently at the beginning of their learning processes, and their first and second IBL sequence clusters emerged notably later with different content compared with the groups in the script scaffolded and non-scaffolded conditions. Moreover, the similar findings of TLDA and TLSA in the script scaffolded and non-scaffolded conditions indicated that if the students ignored the scaffold from the beginning of the CSCIL process, they also did not utilise it later. Overall, these findings illuminate the need for temporal analysis revealing *how* differences emerge between the scaffolded and non-scaffolded conditions, which may benefit refining or re-implementing scaffolds.

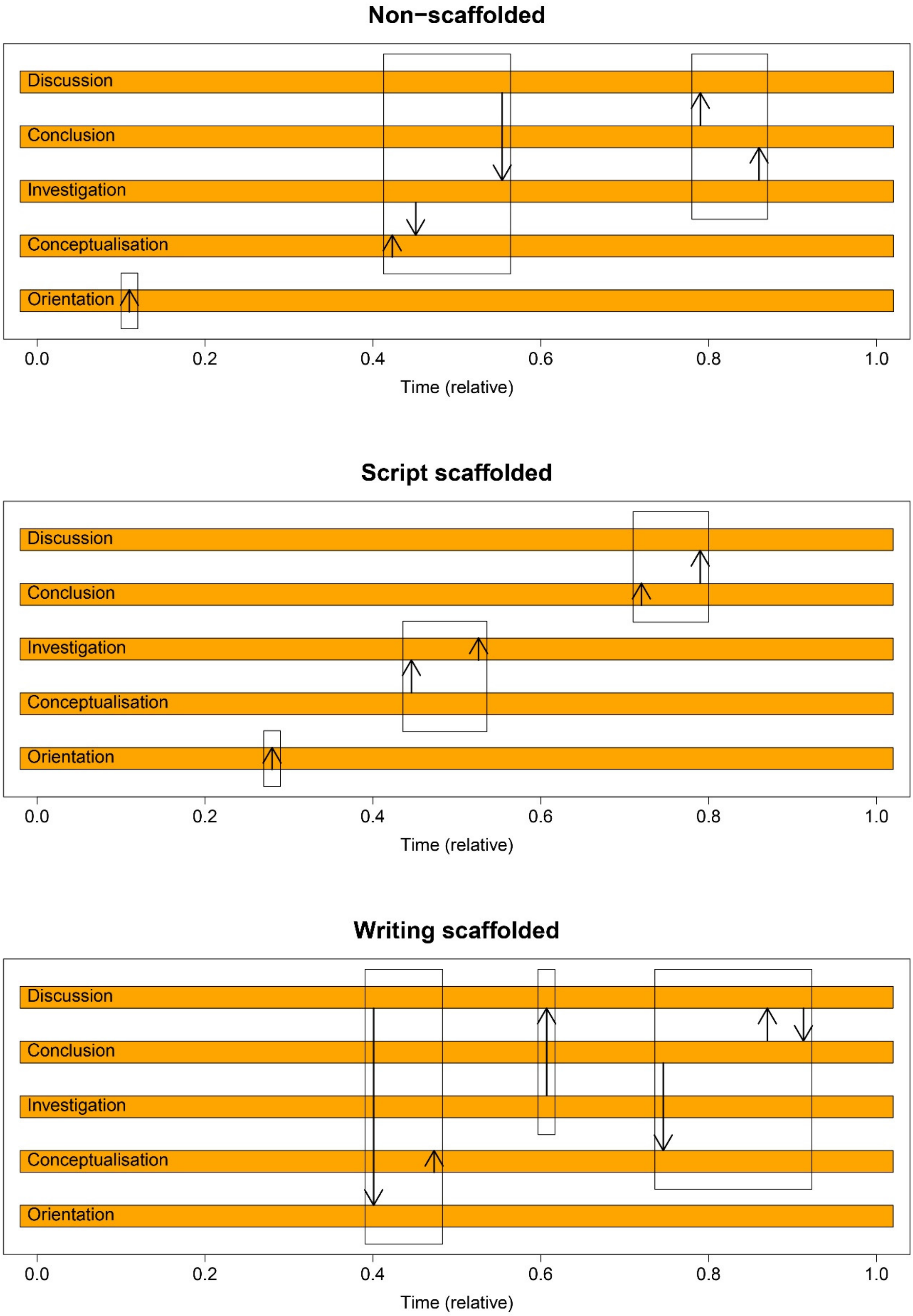


FIGURE 6 The results of temporal lag sequential analysis showing the inquiry-based learning sequences with Yule's $Q > 0.3$ in the scaffolded and non-scaffolded conditions over time. Three inquiry-based learning sequence clusters have been marked with rectangles

7 DISCUSSION

Studies focusing on the temporal aspects of CSCL have increasingly been published; therefore, in addition to finding the relationships amongst variables and judging the statistical effectiveness of interventions, we can now better understand *how* those relationships and effects emerge during CSCL (Stahl, 2017). Thus, in this dissertation, I did not aim to establish the relationships amongst variables or to study their co-variations (see Reimann, 2019); instead, I developed the temporal analysis for CSCL in the context of scaffolded inquiry. My theoretical aim was to develop a temporal analysis procedure for CSCL (sub-study I). The procedure can be used as a roadmap for both theory-driven studies and methodological experiments focusing on the temporal aspects of CSCL; thus, the future studies can be more commensurable (as is the case in the studies focusing on the variable-centred variance theory, which makes it possible to conduct meta-analyses, for example). Through commensurable replications, we can begin synthesising the temporal aspects of CSCL, which are related to the studied variables (e.g. learning outcomes, attitudes and motivation) – that is, we can determine if the temporal aspects of CSCL are sequences or co-occurrences of some events over time or the duration of some events over time that matter. The temporal analysis of CSCL may also help us in designing better technologies and pedagogical approaches for CSCL because the advantages of collaborative learning and computer-support, in general, have been acknowledged (Chen et al., 2018).

IBL has been a potential and popular pedagogical approach in CSCL settings for developing knowledge that future natural scientists need (Jeong et al., 2019). My methodological aim was to advance the temporal analysis methods to study CSCIL (sub-studies III and IV). To enhance CSCIL in the practice phase of the primetime learning model (sub-study II), my empirical aim was to design scaffolds (sub-study III) and analyse their role in the CSCIL (sub-study IV) based on the temporal analysis procedure and advanced methods. I summarise the relations between sub-studies I, III and IV in TABLE 1. Temporal analysis may benefit scaffolding CSCIL by showing *how* learning occurs and *how* differences emerge between the scaffolded and non-scaffolded conditions. In addition to designing scaffolds, the information about the temporal aspects can be used for refining and re-implementing scaffolds. For example, comparing the temporal aspects of scaffolded and non-scaffolded CSCIL can reveal whether the minor differences between the two conditions are because of the poor design of the scaffold or because the students ignore the scaffold. These findings can be used to refine the scaffolds (in the case of poor design) or to consider their novel implementation (in the case of students ignoring the scaffold).

In the following two sections, I describe my reflections on the theoretical (section 7.1), methodological and empirical (section 7.2) contributions of this study.

7.1 Reflections on the temporal analysis procedure for CSCL

Relating to the theoretical aim, the temporal analysis procedure was based on six key operations (sub-study I and sections 5.1–5.6). The first key operation is to specify the temporal aspects that are studied to address the theoretically framed research aims. In this study, I broadly defined the temporal aspects of CSCL as focusing on the characteristics of or interrelations between events over time. This definition highlights the premise of the temporal analysis: characteristics of or interrelations between events over time are more important than the presence or absence of the events in isolation (cf. e.g. Shaffer et al., 2016). The second key operation, forming a context for the study, can be characterised with learner interaction, technological resources used to mediate the interaction and what ideas and thoughts students are working with. The third key operation is to collect process data. The specification of the theoretically framed research aims regarding the temporal aspects of CSCL decreases the pitfalls of the third key operation. This role of theoretical framing is important because a bigger size of process data makes it easier to find statistically significant but theoretically meaningless patterns from the data (Wise & Shaffer, 2015).

In the fourth key operation, events are conceptualised from the process data. This operation is at the core of temporal analysis because it determines the level of temporal granularity of the analysis (Molenaar, 2014) – that is, researchers decide how much to zoom in or out to address the theoretically framed research aims. According to the timescales of different learning processes developed by Lemke (2000, p. 277), an event can (in theory) last whatever from chemical synthesis to universal change. Different types of events can also be conceptualised from the same process data, as I have done in sub-study III from the transcriptions of screen-capture video and audio recordings: communication episodes (a few utterances) captured the IBL phase, whereas communication units (an utterance) captured students' ways of using the Python program (TABLE 1).

The fifth key operation is to employ temporal analysis methods after researchers have decided what counts as an event. In sub-study I, I critically analysed the differences and commonalities amongst the different temporal analysis methods, which Molenaar (2014), for example, has called for. When choosing the appropriate method, again, it is crucial to keep in mind the specified temporal aspects of CSCL that have to be studied from the events to address the research aims. The sixth key operation is to interpret the outcomes based on the chosen temporal analysis methods by conducting possible data and method triangulation. Note that temporal analysis may require interdisciplinary research collaboration to ensure that the data and methods are properly chosen and employed and that the results are accurately interpreted (Wise & Schwarz, 2017). It is no longer rare that a learning scientist, a computer scientist and an expert in signal processing work together to better understand learning as a process unfolding over time.

Although the proposed key operations for analysing the temporal aspects of CSCL can provide a roadmap for future studies, there is still a need to adapt the operations to different theoretical and methodological frameworks in CSCL research. For example, Van Laer and Elen (2018) proposed a framework for sequence analysis in the field of self-regulated learning. Next, I offer my reflections on the first steps that I took when implementing the key operations to study the temporal aspects of CSCL in the context of scaffolded inquiry.

7.2 Reflections on the temporal analysis of computer-supported collaborative inquiry-based learning

With respect to the methodological aim and advancing temporal analysis methods to study CSCIL (sub-studies III and IV), the question may arise of whether there should be theoretically framed research aims that guide the development of methods. However, I agree with Reimann (2019, p. 4), who noted that available methods always play a role in the research aims proposed and explanations suggested. When visualising the CSCIL processes of two groups in sub-study III (n = 10), I found that the most frequent IBL sequences characterised the challenges and productive practices of these groups. Without information about the time instants of the sequences, however, the interpretation of the sequences became challenging. First, although another group in sub-study III (see FIGURE 4) had the most frequent sequence between the orientation and investigation phases, orienting and investigating, or even the sequence itself, were not enhancing or hindering CSCIL; however, the temporal emergences of this sequence around the mid-point of the CSCIL process might have caused some group members to experience frustration (cf. Perez et al., 2017). This frustration probably contributed to making conclusions without data supporting any of the options given and thus led to an incorrect solution.

Second, monitoring the time instants of the sequences was necessary from the viewpoint of studying the intertwining role of the Python program in these sequences. The group's challenges to implement the planned data collection activities (the deep-level use of the Python program in the investigation phase) in their practice (the surface-level use of the Python program in the investigation phase; see TABLE 2 and FIGURE 4) were temporally intertwined with the most frequent sequence between the orientation and investigation phases.

Third, the time instants of the sequences helped in finding the general progress of learning, as individual sequences are sometimes challenging to interpret (Csanadi et al., 2018). I implemented this idea of studying the general progress of CSCIL in sub-study IV, in which I developed TLSA. TLSA showed how the IBL sequences that had at least moderate positive association emerged as a function of time. TLSA together with TLDA enabled me to study the intertwining role of the Python program in the IBL sequences of 46 groups (*N* = 231). An advantage of both the visualisations and TLSA is that these methods combine the different conventions to refer to temporality (section 3.2): I showed how the IBL sequences emerged as time flows (Knight et al., 2017) in an authentic higher education context.

With respect to the empirical aim, I analysed the temporal aspects of CSCIL to design scaffolds (sub-study III) and analyse their role in CSCIL (sub-study IV) because researchers widely see scaffolding as crucial to achieve the benefits of CSCIL. In the context of the practice phase of the primetime learning model (sub-study II), scaffolds implemented in the technological learning environment can be beneficial because no teacher is present in these group working sessions. When designing scaffolds, I focused on the random walk problem (FIGURE 3), in which students had to (i) run the Python program with different values of the number of collisions and (ii) run the Python program multiple times with the same value of the number of collisions to infer the time dependence of the averaged value of the displacement. I recognised students' challenges when making connections between the concepts and variables of the random walk assignment and the representations of those concepts and variables in the video, Python program and output of the Python program (TABLE 3). These challenges emerged, for example, as repetitive sequences between the orientation and investigation phases, which were intertwined with the students' ways of using the Python program (FIGURE 4).

Regarding the design of the scaffolds, first, I aimed to address the identified challenges by scaffolding 'sense-making' as a science inquiry component (Quintana et al., 2004). I provided guiding questions to make connections between the assignment, video and Python program. Second, I scaffolded 'process management' as a science inquiry component (Quintana et al., 2004). I provided implicit task decompositions for the different IBL phases. Finally, I scaffolded 'articulation and reflection' as a science inquiry component (Quintana et al., 2004). I fostered justifications and joint planning. As a result, I designed the writing and script scaffolds, as shown in TABLE 3, and implemented them in the technological learning environment.

Findings of sub-study IV showed no differences in the descriptive statistics regarding the use of the Python program amongst the writing scaffolded, script scaffolded and non-scaffolded conditions. However, TLDA revealed that the temporal use of the Python program in the writing scaffolded condition differed from that in the script scaffolded and non-scaffolded conditions (FIGURE 5): the writing scaffold guided groups to use the Python program more frequently at the beginning of CSCIL. To interpret whether and how this temporal difference in the students' ways of using the Python program emerged in their face-to-face interaction, I conducted TLSA (FIGURE 6). TLSA results revealed three temporally separate IBL sequence clusters, which captured the general progress of CSCIL (cf. the IBL framework by Pedaste et al., 2015, p. 56). This general progress was similar in the writing scaffolded, script scaffolded and non-scaffolded conditions, but the actual content and temporal emergence of the IBL sequence clusters in the writing scaffolded condition differed from those of the IBL sequence clusters in the other conditions. The findings of TLDA and TLSA reveal that the writing scaffold played the most significant role at the beginning of CSCIL. In the writing scaffolded condition, after the students familiarised themselves with the Python program at the beginning of CSCIL, the first IBL sequence cluster emerged notably later with more diverse content compared with the other conditions. In the writing scaffolded condition, the orientation phase was associated with the discussion phase, and the conceptualisation occurred temporally close to the orientation phase.

In the script scaffolded condition and particularly in the non-scaffolded condition, the first IBL sequence cluster associated with the orientation phase occurred temporally separate from the other IBL sequence clusters. In the non-scaffolded condition (and partly in the script scaffolded condition), this first IBL sequence cluster emerged before the students started familiarising themselves with the Python program, which was a desirable outcome of the orientation phase (see TABLE 3). Contrary to the writing scaffolded condition, the conceptualisation phase was temporally part of the IBL sequence cluster associated with the investigation phase in the script scaffolded and non-scaffolded conditions. The third IBL sequence cluster associated with the conclusion and discussion phases emerged at the same time in all three conditions. Thus, the differences amongst the conditions decreased towards the end of the CSCIL processes, which highlighted the need to account for the temporal aspects in the context of scaffolded inquiry. For example, approaches based on variable-centred variance theory assume independent variables continuously acting on dependent variables as a function of time (Reimann, 2009).

Regarding the role of the writing scaffold in CSCIL, this scaffold encouraged a 'think-before-act' attitude in face-to-face interaction, which has been seen as an advantage of asynchronous online discussions (Clark et al., 2003; Cohen & Scardamalia, 1998; Veerman et al., 2000; Zion, 2008; Zion et al., 2005). Moreover, it seemed to foster reflection in the groups because sequences associated with the discussion phase were present throughout the CSCIL processes in the writing scaffolded condition (reflection-in-action, Pedaste et al., 2015, p. 57). Regarding the role of the script scaffold in CSCIL, it seems that students ignored the script scaffold from the very beginning of the CSCIL process (see details in sub-study IV). This indicates a need to reconsider the implementation of the script scaffold to ensure that students will engage in the different roles given by the script. Temporal analysis could then be an effective approach to study the differences between the learning activities that the script is designed to foster and the activities that actually take place in the script scaffolded condition (see Dillenbourg & Jermann, 2007; Kobbe et al., 2007).

7.3 Ethical reflections

When conducting this study, I followed the ethical guidelines of the Finnish Advisory Board of Research Integrity (2012). The participants of my study were adults (over 18 years of age), and they gave written consent regarding their participation in the study. The participants were informed that they were free to opt out of the study at any time, both in the written consent and orally when presenting the purpose of the study in an understandable way. I was a teacher for two of the three courses from where the data were collected; however, I was not present in the practice phase of the primetime learning model (sub-study II), which was the focus of this study. I taught the follow-up groups, who video- and audio-recorded their group working sessions, so none the groups lacked extra attention from me because of their participation in the study. In the joint meetings between a group and me, we occasionally talked about the technical problems regarding data collection (e.g. the microphone of the laptop did not work correctly); otherwise, the research did not affect the teaching that the follow-up groups received. In the transcriptions based on the screen-capture video and audio data (sub-studies III and IV), I used pseudonyms. Log data in sub-study IV were analysed in a way that individual groups and students could not be recognised. The data were collected in 2016 and 2017 and were stored according to the University's Ethic Committee Guidelines of that time.

7.4 Limitations and reflections on the reliability and validity

The outcomes of my study advance the temporal analysis of CSCL and illuminate the potential of the developed temporal analysis methods in the context of scaffolded inquiry; however, the study also has some limitations. First, the temporal analysis procedure and key operations (sub-study I) were based on a broad range of prior research (systematic literature review of 78 articles) that increases their validity to study the temporal aspects of CSCIL in sub-studies III and IV. However, the key operations were temporally the last outcome of my PhD studies; therefore, I could have more thoroughly elaborated the choices in some operations. In particular, different implementations of the key operations (e.g. different conceptualisations of events or temporal analysis methods) might have provided a different lens through which the challenges in the students' CSCIL processes could have differently appeared (see also Chen et al., 2019; Dalland et al., 2020). For example, TLSA labelled one time instant for each IBL sequence, so the findings of TLSA did not allow studying possible repeated loops amongst the different IBL phases in sub-study IV. To increase the reliability and validity of the findings, I used different data sources (screen-capture videos, audio recordings and log data), conceptualisations of events (communication episodes and units and non-verbal activities showing the runs with the Python program with the timestamps) and methods (visualisations, TLSA and TLDA) in sub-studies III and IV (see TABLE 1). I also made these choices and implementations in the different key operations transparent.

Second, the inter-rater agreement, when coding the events to the different IBL phases in sub-studies III and IV, showed that capturing 'units of meaning' (Henri, 1992, p. 134) – that is, communication episodes – from the transcriptions was not unambiguous. To improve the reliability of the findings, I created coding manuals presenting example episodes from each IBL phases along with the reasoning for why the example captured a 'unit of meaning'. To guarantee the validity of the coding, I chose the example episodes from the original transcriptions. These coding manuals are provided in sub-studies III and IV to make the coding procedure transparent. Moreover, one researcher, in addition to me, independently coded communication episodes to the different IBL phases (see details in sub-studies III and IV). Because the different IBL activities are not separate but may overlap and interconnect (Rönnebeck et al., 2016), a communication episode might also include the characteristics of the different IBL phases. Thus, the differences amongst the IBL phases were sometimes unclear, particularly when considering the distinctions between the orientation and conceptualisation phases. These disagreements were resolved on demand in the common meetings with all the co-authors of sub-studies III and IV.

Third, when examining the groups' IBL sequences and their ways of using the Python program, I did not evaluate the groups' different activities when presenting the outcomes in sections 6.1.6 and 6.2.6. For example, when students formulated research questions or hypotheses for the random walk problem in the conceptualisation phase, I did not consider the rationality or format of the questions or hypotheses. Again, to improve reliability and validity, I used different data sources, conceptualisation of events and methods: in sub-study III, I assessed individual students' contributions to the CSCIL process by coding whether an utterance moved the group towards or away from the goal of the inquiry. These findings aligned with those presented in section 6.1, as the group that did correctly solve the problem included students moving the group towards the goal, whereas another group included students moving away from the goal.

Finally, I addressed the empirical aim of the study by focusing on one thermodynamics-related problem; therefore, the empirical findings should be generalised to other contexts with caution. Despite these limitations, this study provides many theoretical, methodological and practical implications as well as suggestions for future research, which I describe next.

7.5 Implications and future directions

In terms of theoretical implications, first, this study contributed to establishing practices for analysing the temporal aspects of CSCL by defining the key operations for the analysis of these aspects (sub-study I). On studying the implementations of the key operations (sub-study I and sections 5.1–5.6), I found implicit conceptualisations of the temporal aspects of CSCL. In particular, when the temporal aspects of CSCL are defined as focusing on the characteristics of or interrelations between events over time, the events are related to learner interaction (e.g. who is talking; sub-study III), ideas and thoughts developed during the interaction (e.g. what is talked about; sub-studies III and IV) and the use of technological resources to mediate the interaction (e.g. what non-verbal activities are conducted; sub-studies III and IV). The definition highlights the different aspects present in CSCL (learner interaction, ideas and thoughts developed during the interaction and the use of technological resources to mediate the interaction). Temporal analysis is a tool used to study how these aspects intertwine, leading to better understanding of CSCL as a process unfolding over time. The systematic literature review performed in sub-study I and the review article by Dado and Bodemer (2017) showed that the mediating role of the technological resources is often neglected in CSCL research (see also Bernhard, 2018; Chen et al., 2019). To date, the temporal analysis of CSCL has mostly been based on the sequences of events related to learner online interaction (analysed by conducting social network analysis) and to the ideas and thoughts developed in the online interaction (analysed by conducting sequential analysis). This study attempted to address this research gap by focusing on the mediating role of technological resources when developing ideas and thoughts in CSCIL during face-to-face interaction, but more research is needed in the future.

Second, the results of sub-study IV showed that CSCIL taking place in face-to-face interaction was divided into three temporally separate IBL sequence clusters: the first cluster was associated with the orientation phase, the second with the investigation phase and the third with the conclusion and discussion phases. Although the actual content and temporal emergence of the IBL sequence clusters varied between the scaffolded and non-scaffolded conditions, TLSA was able to capture the general progress of non-linear CSCIL processes. These results illustrated the realised pathways of inquiry in CSCL settings (cf. the IBL framework by Pedaste et al., 2015, p. 56). Moreover, the results based on TLDA (and the findings of sub-study III) indicated that the students' ways of using the available technological resources for inquiry play an important role in the observed sequences and progress of inquiry. In the future, how the observed temporal aspects of CSCIL moderate learning outcomes needs to be examined. In addition, observing the development of IBL sequence clusters and the use of technological resources over longer periods could provide indications about the development of students' inquiry and technological skills.

With respect to methodological implications, first, I advanced temporal analysis methods (visualisations, TLDA and TLSA) to study the temporally intertwining aspects of CSCIL. Visualisations of two groups' CSCIL processes (n = 10 in sub-study III) enabled me to determine how the most frequent IBL sequences and the use of the Python program in these sequences characterised the learning progress. These findings guided the development of TLDA and TLSA, which have the potential to examine CSCIL of large sample sizes (46 groups, N = 231 in sub-study IV). Overall, these methods present information about the temporal aspects of CSCIL in compact and comprehensive ways, which assists in coping with the increased size of data sets. In the future, the methods presented in this study could be applied in other contexts. Moreover, these methods could enhance learning and teaching practices in addition to the research purposes. Because visualisations of CSCIL make learning processes visible from the viewpoint of inquiry and the use of technological resources, they could be used, for example, in group awareness tools. In the meta-analysis by Chen et al. (2018), group awareness tools were seen as one of the most promising ways to enhance both CSCL processes and outcomes (see one practical implementation in Tissenbaum & Slotta, 2019).

Second, this study provides guidelines for designing methodological experiments in a systematic way. In the future, with the help of the proposed key operations for analysing the temporal aspects of CSCL (sub-study I) and advanced methods (sub-studies III and IV), it would be worth considering what kind of process data (e.g. audio, eye-tracking, log, physiological or video data) is needed to address the theoretically framed research aims. The conceptualisation of events from the process data and the choice of temporal analysis methods also play a crucial role in properly addressing the aims.

Regarding practical implications, first, I showed *how* CSCIL occurred in an authentic higher education context (sub-studies III and IV); this may help teachers when they design and implement CSCIL in their instructional practices (sub-study II). In sub-study IV, I illustrated *how* the writing and script scaffolds temporally changed students' CSCIL compared with the non-scaffolded condition by conducting TLDA and TLSA in parallel. In the future, these findings could promote the development of adaptive scaffolding when more information about the associations between the log data and other process data (e.g. video, audio or online discussions) is found. Although the idea of adaptive scaffolding is not new (see e.g. Kollar et al., 2007), research on it is still in progress (de Jong, 2019). Real-time monitoring of CSCIL activities based on log data could lead to the creation of scaffolds or other forms of guidance in real time when a technological learning environment monitors undesired behaviour (see Perez et al., 2017; Popov et al., 2017). Moreover, natural language processing of students' written responses (as in the writing scaffolded condition) could automatically further adapt the scaffolds to the needs of a particular group in face-to-face interaction (see e.g. Uribe et al., 2020). Regarding the development of the primetime learning model (and other learning and teaching approaches; see sub-study II), adaptive scaffolding can further redirect teaching resources to intimate meetings with students.

Second, temporal analysis can provide input when developing the approaches for analysing 'the performance in context' (Shaffer et al., 2009, p. 34; see also Blikstein & Worsley, 2016; Swiecki et al., 2020). Namely, the mastery of basic facts and concepts is not sufficient and students have to learn how to effectively use different resources when solving problems (Jeong & Hmelo-Silver, 2010). For example, numerical problem-solving tools are increasingly important for future natural scientists, but learning to use those tools requires skills from many disciplines (physics, mathematics and computer science; Taub et al., 2015). In the future, collaborative problem-solving associated with numerical problem-solving tools (such as Python programs) could be examined as a construct requiring inquiry, computational thinking and mathematical problem-solving skills (Pedaste et al., 2019), in addition to the generic collaborative problem-solving skills (Hesse et al., 2015). This kind of research could contribute to the development of the practice phase of the primetime learning model (sub-study II) in terms of its CSCIL activities, the scaffolds needed for students to be able to perform the activities and the assessment of CSCIL.

8 CONCLUSIONS

Learning is a dynamic process that unfolds over time (Kapur, 2011; Mercer, 2008). In addition to trying to capture this dynamism with variables and their (co-)variance, analysing the temporal aspects of learning could provide valuable insights into *how* learning occurs. Theoretically, I have developed a temporal analysis procedure for CSCL on the basis of a systematic literature review of 78 journal articles. The procedure includes six key operations for analysing the temporal aspects of CSCL. I applied the procedure in undergraduate physics courses, where IBL is a popular pedagogical approach in CSCL settings. Methodologically, I advanced temporal analysis methods to study CSCIL as a process unfolding over time in face-to-face interaction. Empirically, I designed scaffolds for CSCIL (n = 10, two groups of five students) and then studied their role in CSCIL (N = 231, 46 groups) by employing the proposed key operations and advanced methods.

In this study, first, I found that the challenges and productive practices that occurred when the students used a technological resource for inquiry (the Python program) were temporally intertwined with the specific IBL sequences. For example, the challenge of conducting the planned data collection activities in practice was temporally intertwined with the repetitive sequences between the orientation and investigation phases. I used these results to design writing and script scaffolds that mainly provide procedural assistance with hints on how to use the Python program as a part of CSCIL. I implemented these scaffolds in the technological learning environment. Second, I found the temporal differences amongst the writing scaffolded, script scaffolded and non-scaffolded conditions in the use of the Python program. These differences were associated with the differences in the content and temporal emergence of three IBL sequence clusters. In general, the first cluster was associated with the orientation phase, the second with the investigation phase and the third with the conclusion and discussion phases. The findings showed that the writing scaffold guided the students to familiarise themselves with the Python program before engaging in the inquiry and vice versa for the groups in the script scaffolded and non-scaffolded conditions. The writing scaffold specifically fostered joint thinking and reflection because the discussion was part of every IBL sequence cluster in this condition.

The findings of this study showed that temporal analysis may reveal the aspects of CSCIL that would otherwise be hidden. The adaption of the proposed key operations for analysing the temporal aspects of CSCL may increase the comparability and commensurability of future studies. By paying more attention to the temporal aspects of learning, we can better understand the premises for successful learning.

YHTEENVETO

Tietokoneavusteisen yhteisöllisen oppimisen (eng. computer-supported collaborative learning, CSCL) tutkimus alkoi vertailemalla teknologiatuetussa tai yhteisöllisessä oppimisessa saavutettuja oppimistuloksia teknologiattomaan tai yksin tapahtuvaan oppimiseen. CSCL-tutkimuksessa on selvitetty myös erilaisten teknologisten työkalujen ja laitteiden sekä pedagogisten lähestymistapojen vaikutusta oppimiseen (ks. esim. Chen ym., 2018). Sen lisäksi, että CSCL-tutkimuksessa vastaamme kysymykseen *'mitä oppimista tapahtuu'*, on tärkeä etsiä vastauksia kysymykseen *'miten oppiminen tapahtuu'* (Ludvigsen & Steier, 2019, s. 3). Vastaamalla tähän jälkimmäiseen kysymykseen voimme ymmärtää paremmin, milloin teknologiat ja yhteisöllinen oppiminen edistävät asetettujen tavoitteiden saavuttamista. Koska oppiminen on ajallisesti kehittyvä dynaaminen prosessi (Kapur, 2011; Mercer, 2008), muuttujiin ja niiden vaihteluun (varianssiin ja kovarianssiin) perustuva tutkimus ei välttämättä riitä tämän dynaamisuuden tarkasteluun. Muuttujiin perustuvan tilastollisen päättelyn lisäksi oppimisen ajallinen tarkastelu voi tuottaa hyödyllistä tietoa siitä, *miten* oppiminen tapahtuu.

Väitöskirjani tavoitteena oli kehittää CSCL:n ajallista tarkastelua tuetun tutkivan oppimisen kontekstissa. Teoreettisena tuotoksena kehitin menettelytavan CSCL:n ajalliseen tarkasteluun (osatutkimus I). Menettelytavan kehittäminen perustui systemaattiseen kirjallisuuskatsaukseen, joka sisälsi 78 kansainvälistä vertaisarvioitua tieteellistä artikkelia. Menettelytapa sisälsi kuusi avainoperaatioita, joiden avulla CSCL:n ajallisia näkökulmia voidaan tutkia. Sovelsin menettelytapaa yliopistofysiikan peruskursseilla, joilla oppiminen ja opetus perustuivat primetime learning -toimintamalliin, joka on esitelty yksityiskohtaisesti osatutkimuksessa II. Toimintamallissa keskeisiä ovat viikoittaiset ryhmätunnit, joissa 4–6 opiskelijan ryhmät kokoontuvat kasvokkain ja ratkaisevat teknologisessa oppimisympäristössä olevia ongelmia ilman opettajaa. Luonnontieteiden opetuksessa tutkiva oppiminen on suosittu pedagoginen lähestymistapa CSCL:ää hyödynnettäessä. Ryhmätunnit sisälsivät niin ikään tutkivan oppimisen ongelmia, joiden ratkaisemissa opiskelijat käyttivät erilaisia teknologisia resursseja, muun muassa numeriikkaa (Python-ohjelmia). Metodologisena tuotoksena kehitin oppimisen ajalliseen tarkasteluun menetelmiä, joita hyödynsin tämän tietokoneavusteisen yhteisöllisen tutkivan oppimisen (eng. computer-supported collaborative inquiry-based learning, CSCIL) tarkastelussa (osatutkimukset III ja IV). Empiirisenä tuotoksena suunnittelin tukimuotoja CSCIL:ään (n = 10, kaksi viiden opiskelijan ryhmää) tarkastelemalla, *miten* oppiminen tapahtui (osatutkimus III). Lisäksi tutkin tukimuotojen roolia näissä oppimisprosesseissa (N = 231, 46 ryhmää) tarkastelemalla, *miten* erot tuettujen ja ei-tuettujen ryhmien välille syntyivät ajan edetessä (osatutkimus IV). Empiirisessä osassa hyödynsin kehittämiäni ajallisen tarkastelun avainoperaatioita ja menetelmiä.

Ryhmätuntien haasteet ja toimivat käytänteet, kun ryhmät hyödynsivät teknologisia resursseja (nyt Python-ohjelmaa) tutkivassa oppimisessa, olivat ajallisesti yhteydessä tiettyihin tutkivan oppimisen ketjuihin eli siirtymiin tutkivan oppimisen vaiheiden välillä. Jos ryhmällä oli haasteita esimerkiksi toteuttaa Python-ohjelmalla suunnittelemaansa aineiston keräämistä, tämä haaste ilmeni toistuvana ketjuna tutkimus- ja orientaatiovaiheiden välillä. Hyödynsin näitä tuloksia, kun suunnittelin joko kirjoittamiseen tai skriptaamiseen (eräänlainen käsikirjoitus, joka sisälsi opiskelijoille osoitettuja rooleja) perustuvaa tukea, jotka molemmat tarjosivat opiskelijoille tukea ja vihjeitä, miten edetä ja hyödyntää Python-ohjelmaa eri tutkivan oppimisen vaiheissa. Lisäsin nämä tukimuodot kursseilla käytössä olleeseen teknologiseen oppimisympäristöön.

CSCIL:n ajallinen tarkastelu paljasti tukimuotojen roolista näkökulmia, jotka olisivat jääneet muutoin huomaamatta. Vaikka kaikki ryhmät keräsivät Python-ohjelmalla keskimäärin yhtä paljon aineistoa, kirjoittamiseen perustuva tuki ohjasi ryhmiä tutustumaan Python-ohjelmaan ennen varsinaisen tutkivan oppimisprosessin aloittamista ja päinvastoin skriptaamiseen perustuvassa sekä ei-tukimuotoja sisältäneessä tilanteessa. Nämä ajalliset erot olivat yhteydessä tutkivan oppimisen ketjuryppäiden sisältöön ja havaittuun ajankohtaan oppimisprosessissa. Yleisesti ottaen ensimmäinen rypäs sisälsi orientoitumiseen liittyviä ketjuja, toinen rypäs tutkimiseen liittyviä ketjuja ja kolmas rypäs johtopäätöksiin sekä pohdintaan liittyviä ketjuja. Kirjoittamiseen perustuva tuki edisti ryhmän yhteistä ajattelua ja reflektiota, sillä pohdintaan liittyviä ketjuja oli kaikissa ketjuryppäissä.

Väitöskirjani teoreettisena seurauksena voi olla ajalliseen tarkasteluun keskittyvien tutkimusten vertailtavuuden ja yhteismitallisuuden paraneminen, kun kehittämäni avainoperaatiot edesauttavat ajallisen tarkastelun menettelytapojen vakiinnuttamista. Nämä vakiintuneet menettelytavat voivat lisätä myös teorialähtöisempää tutkimusta, jossa tavoitteena voi olla teorian kehittäminen ajallisen tarkastelun avulla. Väitöskirjani metodologisena seurauksena on uudet ajalliseen tarkasteluun sopivat menetelmät, joita voi soveltaa myös muissa kuin tuetun tutkivan oppimisen konteksteissa. Lisäksi esittelemäni avainoperaatiot CSCL:n ajalliseen tarkasteluun voivat auttaa erilaisten metodologisten kokeilujen suunnittelua. Oppimisen ja opetuksen kehittämisen näkökulmasta väitöskirjani kuvasi, miten CSCIL tapahtuu autenttisessa yliopistokontekstissa. Lisäksi näytin, miten kirjoittamiseen ja skriptaamiseen perustuvat tukimuodot ajallisesti muuttivat CSCIL-prosesseja verrattuna ei-tukea sisältäneeseen tilanteeseen. Erityisesti lokiaineiston ajallinen tarkastelu voi tulevaisuudessa hyödyttää oppimisen oikea-aikaista tukemista, kun lokiaineiston ja muun prosessiaineiston (esimerkiksi videon, äänen tai verkkokeskustelujen) yhteyksiä ymmärretään paremmin (ks. osatutkimuksen IV lisäksi esim. Perez ym., 2017; Popov ym., 2017). Myös luonnollisen kielen käsittelyyn perustuvia menetelmiä voisi hyödyntää kirjoittamiseen perustuvan tuen mukauttamisessa opiskelijoiden kirjoittamien syötteiden perusteella (ks. esim. Uribe ym., 2020). Teknologiaperustaisten tukimuotojen kehittäminen voi edesauttaa esimerkiksi primetime learning -toimintamallin kehittämistä, kun vapautuneita opetusresursseja voi kohdentaa aitoihin kohtaamisiin opiskelijoiden kanssa.

Tulevaisuudessa erilaisia aineistoja ja ajalliseen tarkasteluun sopivia menetelmiä hyödyntämällä oppimisen dynaamisuutta on mahdollista ymmärtää paremmin. Kun kasvatustieteissäkin vakiintunutta muuttujiin perustuvaa tilastollista päättelyä täydennetään oppimisen ajallisella tarkastelulla, voimme ymmärtää paremmin, *miten* hyvää oppimista tapahtuu.

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.

Arnold, J. C., Kremer, K., & Mayer, J. (2014). Understanding students' experiments ─ what kind of support do they need in inquiry tasks? *International Journal of Science Education, 36*(16), 2719–2749.

Bannert, M., Reimann, P., & Sonnenberg, C. (2014). Process mining techniques for analysing patterns and strategies in students' self-regulated learning. *Metacognition and Learning, 9*(2), 161–185.

Barbera, E., Gros, B., & Kirschner, P. (2015). Paradox of time in research on educational technology. *Time & Society, 24*(1), 96–108.

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.

Belland, B. R., Walker, A. E., & Kim, N. J. (2017a). A Bayesian network meta-analysis to synthesize the influence of contexts of scaffolding use on cognitive outcomes in STEM education. *Review of Educational Research, 87*(6), 1042–1081.

Belland, B. R., Walker, A. E., Kim, N. J., & Lefler, M. (2017b). Synthesizing results from empirical research on computer-based scaffolding in STEM education. *Review of Educational Research, 87*(2), 309–344.

Bernhard, J. (2018). What matters for students' learning in the laboratory? Do not neglect the role of experimental equipment! *Instructional Science, 46*(6), 819–846.

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.

Bybee, R. W., Taylor, J. A., Gardner, A., Van Scotter, P., Powell, J. C., Westbrook, A., & Landes, N. (2006). *The BSCS 5E instructional model: Origins and effectiveness*. BSCS.

Chang, C.-J., Chang, M.-H., Liu, C.-C., Chiu, B.-C., Fan Chiang, S.-H., Wen, C.-T., Hwang, F.-K., Chao, P.-Y., Chen, Y.-L., & 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.

Chen, J., Wang, M., Kirschner, P. A., & Tsai, C. (2018). The role of collaboration, computer use, learning environments, and supporting strategies in CSCL: A Meta-Analysis. *Review of Educational Research*, *88*(6), 799–843.

Chen, Y., Andrews, C. D., Hmelo-Silver, C. E., & D'Angelo, C. (2020). Coding schemes as lenses on collaborative learning. *Information and Learning Sciences*, *121*(1–2), 1–18.

Chiang, T. H. C., Yang, S. J. H., & Hwang, G. (2014). Students' online interactive patterns in augmented reality-based inquiry activities. *Computers & Education, 78*, 97–108.

Chiu, M. M., & Khoo, L. (2005). A new method for analyzing sequential processes. *Small Group Research*, *36*(5), 600–631.

Clark, D. J., Weinberger, A., Jucks, R., Spitulnik, M., & Wallace, R. (2003). Designing effective science inquiry in text-based computer-supported collaborative learning environments. *International Journal of Educational Policy, Research, & Practice*, *4*(1), 55–82.

Cohen, A., & Scardamalia, M. (1998). Discourse about ideas: Monitoring and regulation in face-to-face and computer-mediated environments. *Interactive Learning Environments*, *6*(1–2), 93–113.

Cress, U., Rosé, C. P., Law, N., & Ludvigsen, S. (2019). Investigating the complexity of computer-supported collaborative learning in action. *International Journal of Computer-Supported Collaborative Learning*, *14*(2), 137–142.

Csanadi, A., Eagan, B., Kollar, I., Shaffer, D. W., & Fischer, F. (2018). When coding-and-counting is not enough: Using epistemic network analysis (ENA) to analyze verbal data in CSCL research. *International Journal of Computer-Supported Collaborative Learning*, *13*(4), 419–438.

Dado, M., & Bodemer, D. (2017). A review of methodological applications of social network analysis in computer-supported collaborative learning. *Educational Research Review*, *22*, 159–180.

Dalland, C. P., Klette, K., & Svenkerud, S. (2020). Video studies and the challenge of selecting time scales. *International Journal of Research & Method in Education*, *43*(1), 53–66.

Davis, J. A. (1971). *Elementary survey analysis* (1st ed.). Prentice-Hall.

de Jong, T. (2019). Moving towards engaged learning in STEM domains; there is no simple answer, but clearly a road ahead. *Journal of Computer Assisted Learning*, *35*(2), 153–167.

de Jong, T., Lazonder, A. W., Pedaste, M., & Zacharia, Z. C. (2018). Simulations, games and modelling tools for learning. In F. Fischer, C. E. Hmelo-Silver, S. R. Goldman & P. Reimann (Eds.), *International handbook of the learning sciences* (pp. 241–268). Routledge.

de Jong, T., & Lazonder, A. W. (2014). The guided discovery learning principle in multimedia learning. In R. E. Mayer (Ed.), *The Cambridge handbook of multimedia learning* (pp. 371–390). Cambridge University Press.

de Jong, T., & Van Joolingen, W. R. (1998). Scientific discovery learning with computer simulations of conceptual domains. *Review of Educational Research*, *68*(2), 179–201.

Dillenbourg, P. (1999). What do you mean by 'collaborative learning'? In P. Dillenbourg (Ed.), *Collaborative-learning: Cognitive and computational approaches* (pp. 1–15). Pergamon, Elsevier Science.

Dillenbourg, P., & Jermann, P. (2007). Designing integrative scripts. In F. Fischer, I. Kollar, H. Mandl & J. M. Haake (Eds.), *Scripting computer-supported collaborative learning. Computer-supported collaborative learning* (Vol. 6, pp. 275–301). Springer.

Education Statistics Finland. (2020). *Pass rates of students in university education*. https://vipunen.fi/en-gb/university/Pages/Aloittaneiden-l%C3%A4p%C3%A4isy.aspx

Fang, S., Hsu, Y., & Hsu, W. H. (2016). Effects of explicit and implicit prompts on students' inquiry practices in computer-supported learning environments in high school earth science. *International Journal of Science Education*, *38*(11), 1699–1726.

Finnish Advisory Board of Research Integrity. (2012). *Responsible conduct of research and procedures for handling allegations of misconduct in Finland*. Helsinki: Finnish Advisory Board of Research Integrity. https://www.tenk.fi/sites/tenk.fi/files/HTK_ohje_2012.pdf

Fu, Q., & Hwang, G. (2018). Trends in mobile technology-supported collaborative learning: A systematic review of journal publications from 2007 to 2016. *Computers & Education*, *119*, 129–143.

Gijlers, H., & de Jong, T. (2013). Using concept maps to facilitate collaborative simulation-based inquiry learning. *Journal of the Learning Sciences*, *22*(3), 340–374.

Gijlers, H., Saab, N., van Joolingen, W. R., de Jong, T., & van Hout-Wolters, B. H. A. M. (2009). Interaction between tool and talk: How instruction and tools support consensus building in collaborative inquiry-learning environments. *Journal of Computer Assisted Learning*, *25*(3), 252–267.

Haataja, E., Malmberg, J., & Järvelä, S. (2018). Monitoring in collaborative learning: Co-occurrence of observed behavior and physiological synchrony explored. *Computers in Human Behavior*, *87*, 337–347.

Hämäläinen, R., & Vähäsantanen, K. (2011). Theoretical and pedagogical perspectives on orchestrating creativity and collaborative learning. *Educational Research Review*, *6*(3), 169–184.

Henri, F. (1992). Computer conferencing and content analysis. In A. R. Kaye (Ed.), *Collaborative learning through computer conferencing. The Najadan Papers* (pp. 117–136). Springer-Verlag.

Hesse, F., Care, E., Buder, J., Sassenberg, K., & Griffin, P. (2015). A framework for teachable collaborative problem solving skills. In P. Griffin & E. Care (Eds.), *Assessment and teaching of 21st century skills: Methods and approach* (pp. 37–56). Springer.

Hmelo-Silver, C. E., Duncan, R. G., & Chinn, C. A. (2007). Scaffolding and achievement in problem-based and inquiry learning: A response to Kirschner, Sweller, and Clark (2006). *Educational Psychologist*, *42*(2), 99–107.

Ibáñez, M., & Delgado-Kloos, C. (2018). Augmented reality for STEM learning: A systematic review. *Computers & Education*, *123*, 109–123.

Järvelä, S., Järvenoja, H., & Malmberg, J. (2019). Capturing the dynamic and cyclical nature of regulation: Methodological progress in understanding socially shared regulation in learning. *International Journal of Computer-Supported Collaborative Learning*, *14*(4), 425–441.

Järvelä, S., Veermans, M., & Leinonen, P. (2008). Investigating student engagement in computer-supported inquiry: A process-oriented analysis. *Social Psychology of Education*, *11*(3), 299.

Jensen, J. L., & Lawson, A. (2011). Effects of collaboration and inquiry on reasoning and achievement in 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.

Jeong, H., Hmelo-Silver, C. E., & Jo, K. (2019). Ten years of computer-supported collaborative learning: A meta-analysis of CSCL in STEM education during 2005–2014. *Educational Research Review*, *28*, 100284.

Jeong, H., Hmelo-Silver, C., & Yu, Y. (2014). An examination of CSCL methodological practices and the influence of theoretical frameworks 2005–2009. *International Journal of Computer-Supported Collaborative Learning*, *9*(3), 305–334.

Kaartinen, S., & Kumpulainen, K. (2002). Collaborative inquiry and the construction of explanations in the learning of science. *Learning and Instruction*, *12*(2), 189–212.

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.

Keselman, A. (2003). Supporting inquiry learning by promoting normative understanding of multivariable causality. *Journal of Research in Science Teaching*, *40*(9), 898–921.

Khanlari, A., Resendes, M., Zhu, G., & Scardamalia, M. (2017). Productive knowledge building discourse through student-generated questions. In B. K. Smith, M. Borge, E. Mercier & K. Y. Lim (Eds.), *12th International Conference on Computer Supported Collaborative Learning (CSCL)* (pp. 585–588). International Society of the Learning Sciences.

Kim, M. C., & Hannafin, M. J. (2011). Scaffolding problem solving in technology-enhanced learning environments (TELEs): Bridging research and theory with practice. *Computers & Education*, *56*(2), 403–417.

Knight, S., Wise, A. F., & Chen, B. (2017). Time for change: Why learning analytics needs temporal analysis. *Journal of Learning Analytics*, *4*(3), 7–17.

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.

Kollar, I., Fischer, F., & Slotta, J. D. (2007). Internal and external scripts in computer-supported collaborative inquiry learning. *Learning and Instruction*, *17*(6), 708–721.

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.

Langley, A. (1999). Strategies for theorizing from process data. *Academy of Management Review*, *24*(4), 691–710.

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

Lemke, J. L. (2000). Across the scales of time: Artifacts, activities, and meanings in ecosocial systems. *Mind, Culture, and Activity*, *7*(4), 273–290.

Lin, C., Chiu, C., Hsu, C., Wang, T., & Chen, C. (2018). The effects of computerized inquiry-stage-dependent argumentation assistance on elementary students' science process and argument construction skills. *Journal of Computer Assisted Learning*, *34*(3), 279–292.

Linn, M. C., Clark, D., & Slotta, J. D. (2003). WISE design for knowledge integration. *Science Education*, *87*(4), 517–538.

Lipponen, L., & Hakkarainen, K. (1997). Developing culture of inquiry in computer-supported collaborative learning. In R. Hall, N. Miyake & N. Enyedy (Eds.), *2nd International Conference on Computer Supported Collaborative Learning (CSCL)* (pp. 164–168). International Society of the Learning Sciences.

Ludvigsen, S. (2016). CSCL: Connecting the social, emotional and cognitive dimensions. *International Journal of Computer-Supported Collaborative Learning*, *11*(2), 115–121.

Ludvigsen, S., Cress, U., Rosé, C. P., Law, N., & Stahl, G. (2018). Developing understanding beyond the given knowledge and new methodologies for analyses in CSCL. *International Journal of Computer-Supported Collaborative Learning*, *13*(4), 359–364.

Ludvigsen, S., & Steier, R. (2019). Reflections and looking ahead for CSCL: Digital infrastructures, digital tools, and collaborative learning. *International Journal of Computer-Supported Collaborative Learning*, *14*(4), 1–9.

Lund, K. (2019). Building and regulating cognitive, linguistic, and interactional aspects of knowledge between the individual and the group. *Computers in Human Behavior*, *100*, 370–383.

Mäkitalo-Siegl, K., Kohnle, C., & Fischer, F. (2011). Computer-supported collaborative inquiry learning and classroom scripts: Effects on help-seeking processes and learning outcomes. *Learning and Instruction*, *21*(2), 257–266.

Malmberg, J., Haataja, E., Seppänen, T., & Järvelä, S. (2019). Are we together or not? The temporal interplay of monitoring, physiological arousal and physiological synchrony during a collaborative exam. *International Journal of Computer-Supported Collaborative Learning*, *14*(4), 467–490.

Matuk, C., & Linn, M. C. (2018). Why and how do middle school students exchange ideas during science inquiry? *International Journal of Computer-Supported Collaborative Learning*, *13*(3), 263–299.

Medina, R., & Suthers, D. (2013). Inscriptions becoming representations in representational practices. *Journal of the Learning Sciences*, *22*(1), 33–69.

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

Molenaar, I. (2014). Advances in temporal analysis in learning and instruction. *Frontline Learning Research*, *2*(4), 15–24.

Molenaar, I., & Chiu, M. M. (2017). Effects of sequences of cognitions on group performance over time. *Small Group Research*, *48*(2), 131–164.

Noroozi, O., Weinberger, A., Biemans, H. J. A., Mulder, M., & Chizari, M. (2012). Argumentation-based computer supported collaborative learning (ABCSCL): A synthesis of 15 years of research. *Educational Research Review*, *7*(2), 79–106.

Oner, D. (2013). Analyzing group coordination when solving geometry problems with dynamic geometry software. *International Journal of Computer-Supported Collaborative Learning*, *8*(1), 13–39.

Pea, R. D. (1993). Learning scientific concepts through material and social activities: Conversational analysis meets conceptual change. *Educational Psychologist*, *28*(3), 265–277.

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

Pedaste, M., Palts, T., Kori, K., Sõrmus, M., & Leijern, Ä. (2019). Complex problem solving as a construct of inquiry, computational thinking and mathematical problem solving. *19th International Conference on Advanced Learning Technologies (ICALT) IEEE*, 227–231.

Perez, S., Massey-Allard, J., Butler, D., Ives, J., Bonn, D., Yee, N., & Roll, I. (2017). Identifying productive inquiry in virtual labs using sequence mining. In E. André, R. Baker, X. Hu, M. M. T. Rodrigo & B. du Boulay (Eds.), *Artificial Intelligence in Education* (pp. 287–298). Springer International Publishing.

Popov, V., Leeuwen, A., & Buis, S. C. A. (2017). Are you with me or not? Temporal synchronicity and transactivity during CSCL. *Journal of Computer Assisted Learning*, *33*(5), 424–442.

Quintana, C., Reiser, B. J., Davis, E. A., Krajcik, J., Fretz, E., Duncan, R. G., Kyza, E., Edelson, D., & Soloway, E. (2004). A scaffolding design framework for software to support science inquiry. *Journal of the Learning Sciences*, *13*(3), 337–386.

Radkowitsch, A., Vogel, F., & Fischer, F. (2020). Good for learning, bad for motivation? A meta-analysis on the effects of computer-supported collaboration scripts. *International Journal of Computer-Supported Collaborative Learning*, *15*(1), 5–47.

Raes, A., Schellens, T., De Wever, B., & Vanderhoven, E. (2012). Scaffolding information problem solving in web-based collaborative inquiry learning. *Computers & Education*, *59*(1), 82–94.

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.

Rebetez, C., Bétrancourt, M., Sangin, M., & Dillenbourg, P. (2010). Learning from animation enabled by collaboration. *Instructional Science*, *38*(5), 471–485.

Reimann, P. (in press). Methodological progress in the study of self-regulated learning enables theory advancement. *Learning and Instruction*, 101269.

Reimann, P. (2009). Time is precious: Variable- and event-centred approaches to process analysis in CSCL research. *International Journal of Computer-Supported Collaborative Learning*, *4*(3), 239–257.

Reiser, B. J., & Tabak, I. (2014). Scaffolding. In R. K. Sawyer (Ed.), *The Cambridge handbook of the learning sciences* (pp. 44–62). Cambridge University Press.

Rönnebeck, S., Bernholt, S., & Ropohl, M. (2016). Searching for a common ground – a literature review of empirical research on scientific inquiry activities. *Studies in Science Education*, *52*(2), 161–197.

Schneider, B., & Pea, R. (2013). Real-time mutual gaze perception enhances collaborative learning and collaboration quality. *International Journal of Computer-Supported Collaborative Learning*, *8*(4), 375–397.

Shaffer, D. W., Hatfield, D., Svarovsky, G. N., Nash, P., Nulty, A., Bagley, E., Frank, K., Rupp, A. A., & Mislevy, R. (2009). Epistemic network analysis: A prototype for 21st-century assessment of learning. *International Journal of Learning and Media*, *1*(2), 33–53.

Shamseer, L., Moher, D., Clarke, M., Ghersi, D., Liberati, A., Petticrew, M., Shekelle, P., Stewart, L. A., & the PRISMA-P Group. (2015). Preferred reporting items for systematic review and meta-analysis protocols (PRISMA-P) 2015: Elaboration and explanation. *BMJ*, *349*(7647), 1–25.

Sharma, P., & Hannafin, M. J. (2007). Scaffolding in technology-enhanced learning environments. *Interactive Learning Environments*, *15*(1), 27–46.

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.

Slotta, J. D. (2004). The web-based inquiry science environment (WISE): Scaffolding teachers to adopt inquiry and technology. In M. C. Linn, P. Bell & E. Davis (Eds.), *Internet environments for science education* (pp. 203–232). Erlbaum.

Stahl, G. (2017). Group practices: A new way of viewing CSCL. *International Journal of Computer-Supported Collaborative Learning*, *12*(1), 113–126.

Stahl, G., Koschmann, T., & Suthers, D. (2014a). Computer-supported collaborative learning: An historical perspective. In R. K. Sawyer (Ed.), *The Cambridge Handbook of the Learning Sciences* (pp. 479–500). Cambridge University Press.

Stahl, G., Ludvigsen, S., Law, N., & Cress, U. (2014b). CSCL artifacts. *International Journal of Computer-Supported Collaborative learning*, *9*(3), 237–245.
Suthers, D. D., Toth, E. E., & Weiner, A. (1997). An integrated approach to implementing collaborative inquiry in the classroom. In R. Hall, N. Miyake & N. Enyedy (Eds.), *2nd International Conference on Computer Supported Collaborative Learning (CSCL)* (pp. 272–279). International Society of the Learning Sciences.
Swiecki, Z., Ruis, A. R., Farrell, C., & Shaffer, D. W. (2020). Assessing individual contributions to collaborative problem solving: A network analysis approach. *Computers in Human Behavior*, *104*, 105876.
Tan, E. (2018). Effects of two differently sequenced classroom scripts on common ground in collaborative inquiry learning. *Instructional Science*, *46*(6), 893–919.
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.
Tinto, V. (1975). Dropout from higher education: A theoretical synthesis of recent research. *Review of Educational Research*, *45*(1), 89–125.
Tissenbaum, M., & Slotta, J. D. (2019). Developing a smart classroom infrastructure to support real-time student collaboration and inquiry: A 4-year design study. *Instructional Science*, *47*(4), 423–462.
Ulriksen, L., Madsen, L. M., & Holmegaard, H. T. (2010). What do we know about explanations for drop out/opt out among young people from STM higher education programmes? *Studies in Science Education*, *46*(2), 209–244.
Uribe P., Jiménez A., Araya R., Lämsä J., Hämäläinen R., & Viiri J. (2020). Automatic content analysis of computer-supported collaborative inquiry-based learning using deep networks and attention mechanisms. In P. Vittorini, T. Di Mascio, L. Tarantino, M. Temperini, R. Gennari & F. De la Prieta (Eds.) *Methodologies and Intelligent Systems for Technology Enhanced Learning, 10th International Conference, Advances in Intelligent Systems and Computing, 1241* (pp. 95–105). Springer International Publishing.
van den Hurk, A., Meelissen, M., & van Langen, A. (2019). Interventions in education to prevent STEM pipeline leakage. *International Journal of Science Education*, *41*(2), 150–164.
van der Zanden, P. J. A. C., Denessen, E., Cillessen, A. H. N., & Meijer, P. C. (2018). Domains and predictors of first-year student success: A systematic review. *Educational Research Review*, *23*, 57–77.
van Joolingen, W. R., de Jong, T., Lazonder, A. W., Savelsbergh, E. R., & Manlove, S. (2005). Co-Lab: Research and development of an online learning environment for collaborative scientific discovery learning. *Computers in Human Behavior*, *21*(4), 671–688.
Van Laer, S., & Elen, J. (2018). Towards a methodological framework for sequence analysis in the field of self-regulated learning. *Frontline Learning Research*, *6*(3), 228–249.

van Riesen, S. A. N., Gijlers, H., Anjewierden, A., & de Jong, T. (2018). The influence of prior knowledge on experiment design guidance in a science inquiry context. *International Journal of Science Education*, *40*(11), 1327–1344.

Veerman, A. L., Andriessen, J. E. B., & Kanselaar, G. (2000). Learning through synchronous electronic discussion. *Computers & Education*, *34*(3), 269–290.

Vogel, F., Wecker, C., Kollar, I., & Fischer, F. (2017). Socio-cognitive scaffolding with computer-supported collaboration scripts: A meta-analysis. *Educational Psychology Review*, *29*(3), 477–511.

Vygotsky, L. S. (1978). *Mind in society: The development of higher psychological processes* (1st ed.). Harvard University Press.

Wang, F., & Hannafin, M. J. (2005). Design-based research and technology-enhanced learning environments. *Educational Technology Research and Development*, *53*(4), 5–23.

Wang, H., Duh, H. B., 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.

White, B. Y., & Frederiksen, J. R. (1998). Inquiry, modeling, and metacognition: Making science accessible to all students. *Cognition and Instruction*, *16*(1), 3–118.

Wise, A. F., & Schwarz, B. B. (2017). Visions of CSCL: Eight provocations for the future of the field. *International Journal of Computer-Supported Collaborative Learning*, *12*(4), 423–467.

Wise, A. F., & Shaffer, D. W. (2015). Why theory matters more than ever in the age of big data. *Journal of Learning Analytics*, *2*(2), 5–13.

Wood, D., Bruner, J. S., & Ross, G. (1976). The role of tutoring in problem solving. *Journal of Child Psychology and Psychiatry*, *17*(2), 89–100.

Zacharia, Z. C., Manoli, C., Xenofontos, N., de Jong, T., Pedaste, M., van Riesen, S. A. N., Kamp, E. T., Mäeots, M., Siiman, L., & Tsourlidaki, E. (2015). Identifying potential types of guidance for supporting student inquiry when using virtual and remote labs in science: A literature review. *Educational Technology Research and Development*, *63*(2), 257–302.

Zion, M. (2008). On line forums as a 'Rescue Net' in an open inquiry process. *International Journal of Science and Mathematics Education*, *6*(2), 351–375.

Zion, M., Michalsky, T., & Mevarech, Z. R. (2005). The effects of metacognitive instruction embedded within an asynchronous learning network on scientific inquiry skills. *International Journal of Science Education*, *27*(8), 957–983.

ORIGINAL PAPERS

I

WHAT DO WE DO WHEN WE ANALYSE THE TEMPORAL ASPECTS OF COMPUTER-SUPPORTED COLLABORATIVE LEARNING? A SYSTEMATIC LITERATURE REVIEW

by

Joni Lämsä, Raija Hämäläinen, Pekka Koskinen, Jouni Viiri, & Emilia Lampi

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II

PRIMETIME LEARNING: COLLABORATIVE AND TECHNOLOGY-ENHANCED STUDYING WITH GENUINE TEACHER PRESENCE

by

Pekka Koskinen, Joni Lämsä, Jussi Maunuksela, Raija Hämäläinen, & Jouni Viiri 2018

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SHORT REPORT Open Access

Primetime learning: collaborative and technology-enhanced studying with genuine teacher presence

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Abstract

Background: Productive learning processes and good learning outcomes can be attained by applying the basic elements of active learning. The basic elements include fostering discussions and disputations, facing alternative conceptions, and focusing on conceptual understanding. However, in the face of poor course retention and high dropout rates, even learning outcomes can become of secondary importance. To address these challenges, we developed a research-based instructional strategy, the *primetime learning* model. We devised the model by organizing the basic elements of active learning into a theory-based four-step study process. The model is based on collaborative and technology-enhanced learning, on versatile formative assessment without a final exam, and on genuine teacher presence through intimate meetings between students and teachers.

Results: We piloted the model in two university physics courses on thermodynamics and optics and observed persistent student activity, improved retention, and good learning outcomes. Feedback suggested that most students were satisfied with the learning experience.

Conclusions: The model suits particularly well for courses that, in addition to the teaching subject itself, focus on teaching balanced study habits and strengthening social integration. By its very construction, it also helps the propagation of research-based instructional strategies. Although the model does contain challenges, it represents a generic framework for learning and teaching that is flexible for further development and applicable to many subjects and levels.

Keywords: Teacher presence, Instructional strategies, Collaborative learning, Technology-enhanced learning

Introduction

Science education research has been focusing on improving learning outcomes (Deslauriers et al. 2011; Freeman et al. 2014; Hake 1998). The outcomes have been measured by how well students have learned the topics under study, often reported as gains in pre- and posttests (Hake 1998). The research results recurrently urge to avoid passive lecture-type expositions (Burgan 2006) and to favor active learning methods, characterized by students actively interacting with fellow students and material at hand.

For both students and universities, however, learning outcomes are not the only relevant outcomes. They alone do not suffice. First, while teachers adopting research-based instructional strategies report higher gains in tests, too often the adoptions remain unsustainable (Henderson et al. 2012). Second, courses often suffer from poor student retention. Student activities decline as courses advance, and many students abandon courses prematurely. Fallen activities lead to a persistence problem and insinuate the gradual dropping of studying altogether (Waldrop 2015; Zwolak et al. 2017). Third, much related to the previous problem, too often of secondary importance in course designs is the individual student's learning process and the overall learning experience. And yet, own learning experience and satisfaction is crucial for the students themselves.

Therefore, we summoned the central results from contemporary science education research and developed a new research-based instructional strategy, the *primetime learning model*. We aimed for a model that, in addition

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to solid learning outcomes, will improve student retention, promote research-based teaching practices, and provide a positive learning experience. In particular, we aimed for a model that is practical, requires minimal equipment and physical space, and uses valuable and limited instructional resources as efficiently as possible. The model integrates active learning components into a four-step study process, supports social integration and flexibility, and requires no final exam because it draws its power from versatile assessment. The model is transformational in its institutional novelty and assessment philosophy. In this article, in addition to introducing the model, we attempt to answer the following questions: (1) To what extent the model can improve retention and prolong activity compared with much used flipped classroom approach? (2) How well does the assessment function without an exam? (3) How do the students describe the learning experience of the model? Answering these questions helps to develop teaching models that address challenges beyond learning outcomes.

The basic elements of active learning

According to Redish, the characteristics of active learning include student centeredness, laboratories allowing guided discoveries, explicit training for reasoning, and intellectual activities during the class (Redish 2003). Contemporary science education research provides a more detailed list of various basic elements of active learning (Table 1).

The categorization of the elements in the table may not be unique, but the literature does provide guidelines to tell effective learning from ineffective one. Thus, any modern learning model should be a suitable blend of these elements. The sheer knowledge of the basic elements is insufficient, however, as success or failure in teaching hinges on practical implementation and course design, as experienced both by the teachers and the students.

The basic elements in practical course designs

The basic elements can be put into action by various research-based instructional strategies. A few of the well-established strategies in physics include Peer Instruction (Crouch and Mazur 2001; Mazur 1997), Modeling Instruction (Halloun and Hestenes 1987; Hestenes 1987), Cooperative Group Problem Solving (Heller and Heller 1999), Workshop Physics (Laws 1991), Scale-Up (Beichner et al. 2007), Just-In-Time Teaching (Novak et al. 1999), Tutorials in Introductory Physics (McDermott and Shaffer 2002), and many others. While incomplete, this list demonstrates how basic elements can be implemented at varying levels of dedication. The first level consists of course designs, where the basic elements are merely appended on top of traditional lecturing without an integrated approach to reform. While providing a low threshold to activate traditional lectures, this level is vulnerable to unsustainable adoption (Henderson et al. 2012). The second level comprises various types of flipped classroom strategies, where lectures are used for peer instruction or other student-engaging activities after the lectures' topics have been studied at home from videos or textbooks (Crouch and Mazur 2001; Mazur 1997). These methods are much in vogue,

Table 1 The basic elements of active learning and examples for related attitudes and realizations

Basic element	Central findings
Interaction (In)	Allow students to interact with peers and teachers to articulate thoughts and arguments, challenge alternative conceptions, meet mistakes head-on and correct them (Heller et al. 1992; Herrmann 2013; Knight 2004b; Smith et al. 2009; Springer et al. 1999).
Technology enhancement (Te)	Use videos, animations, applets, simulations, and numerical exercises. Technology provides various viewpoints and controls cognitive load under well-instructed usage (De Jong and Njoo 1992; Muller et al. 2007; Schmid et al. 2014; Wagh et al. 2017; Wieman and Perkins 2005; Wieman et al. 2008).
Alternative conceptions (Al)	Do not disregard alternative conceptions, but acknowledge them and face them head-on (Beatty et al. 2006; Muller et al. 2007).
Study phenomena (Ph)	Place phenomena above abstractions and use everyday experiences to keep students on the same track; use context-rich, real-life problems (Heller and Hollabaugh 1992; Wieman and Perkins 2005).
Focus on concepts (Co)	Avoid problems with symbol manipulations and focus on concepts instead. Even math problems sprout on conceptual problems (Dufresne and Gerace 2004; Wieman et al. 2008).
Problem-solving skills (Pr)	Teach and enforce explicit problem-solving strategies (Heller et al. 1992; Heller and Hollabaugh 1992; Maloney 2011; McDermott and Redish 1999; Pedaste et al. 2015).
Self-assessment and reflection (Se)	Train metacognition by systematically promoting reflections (Beatty et al. 2006).
Feedback and formative assessment (Fo)	Give continuous and immediate feedback and build assessment that supports studying while it happens (Beatty and Gerace 2009; Dihoff et al. 2004; Dufresne and Gerace 2004; Hattie and Timperley 2007).
Multiple representations (Re)	Take advantage of context-richness, video and audio, and verbal, mathematical, and graphical representations (Heller and Hollabaugh 1992; Knight 2004a, 2004b; Treagust et al. 2017).
Adaptability (Ad)	Allow flexible and adaptable study tempo and goals and provide personal feedback (Kulik et al. 1990; Raes et al. 2014).

as the course designs are still based on a safe and familiar setting of one teacher meeting the entire class in a class or an auditorium (Andrews et al. 2011). The third level of dedication blurs the distinction between lectures and recitation classes, and the students get immersed in various productive activities that happen in laboratories, studios, or computer classrooms. Related course designs are transformational compared with traditional lecturing and require more dramatic changes to teaching practices.

On large-enrollment classes, the status of the lecture is particularly prominent. Although active elements may make large lectures more engaging, the framework of one teacher and an auditorium full of students is problematic. Discussions are restricted by concerted tempo. The teacher is limited to occasional interactions with a few students, usually in the front rows. While this interaction may help the teacher to tune teaching, most students remain unheeded. Since there is not enough time available for everybody, student conversations may drift off the point, and collaborations succumb to pitfalls that make them unproductive (James and Willoughby 2011). And although brief interactions during lectures may for some students cultivate social integration, for other students they do not; it is easy for students to leave the flipped classroom without lasting social bonds, particularly for the students that otherwise prefer studying alone. In ordinary lectures, the flexibility and adaptability of student activities always remain highly restricted.

There are also other problems. Many strategies focus on restricted aspects of student activities. Some strategies have the downside of requiring dedicated, computer-equipped classrooms, whose high cost may be a hindrance (Dori et al. 2007). Often strategies focus more on student activities, less on assessment (Wieman et al. 2009). Alas, assessment dictates how students direct their study efforts in practice (Snyder 1971). Even with active learning methods, an unfavorably planned assessment can become "the silent killer of learning," as Eric Mazur put it, and undermine teacher's good intentions. In the literature, there are teaching methods that include several basic elements, including social integration, assessment, and multiple practices of student activation (Wells and Hestenes 1995), but we felt that there is a demand for a new method that combines the basic elements with limited institutional requirements and a high degree of practicality.

The primetime learning model

Thus, our goal was to summon all the lessons learned from science education research and to develop a new, practical course design. We wanted the design to (i) include the basic elements of active learning to retain the good learning outcomes; (ii) be based on an assessment that improves student commitment, to promote balanced study load, and to direct students' attention to the study process itself—to where it belongs; and (iii) support social and academic integration to reduce student drop-off (Tinto 1975).

The process of developing and refining the model took well over a year and happened within a university-wide community of 10–20 developing and practicing teachers and researchers from various branches of education research. This process enabled us to achieve both practical and theoretically sound learning model.

Model is based on fixed groups

First, we note that many basic elements in Table 1 can be used efficiently by dividing the students into small groups. Groups provide a natural foundation for peer support (Nussbaum et al. 2009), for engaging activities, for student interactions, for facilitating formative assessment, and for implementing the course design in practice (Enghag et al. 2009; Heller et al. 1992; Springer et al. 1999). Groups are efficient vehicles to support familiarity, integration, and safe environment and to foster the feeling of belonging (Wilcox et al. 2005). These benefits even strengthen when groups are fixed and remain the same throughout the course. The relationships in the groups anchor the students into studying and help to address the persistence problem (Waldrop 2015). Most importantly, acquiring compatible friends through grouping can improve student retention (Salomone and Kling 2017) and lower drop-off rates (Wilcox et al. 2005), the very challenges we aim to address. Thus, our starting point to developing the model was to divide the students into small groups.

Devising a new course design: arranging active learning elements into a timeline

Apart from fixed groups, we founded the new course design upon the theoretical framework of the revised Bloom's taxonomy in knowledge dimension (Anderson and Krathwohl 2001; Krathwohl 2002). In this taxonomy, knowledge is divided into four levels: factual, conceptual, procedural, and metacognitive knowledge. Guided by this taxonomy, we arranged the study process according to four successive but temporally separate steps or sessions. The first session is about gathering and remembering the factual knowledge about a given topic. The second session is about understanding the interrelationships between the facts and about deeper, conceptual understanding. The third session is about procedural knowledge and about the skills of applying the concepts. The fourth session is about metacognitive knowledge, about self-knowledge, and about evaluating and analyzing one's cognition. Each session can also be identified by pertinent cognitive processes (Fig. 1) (Anderson and Krathwohl 2001). These four sessions provide a solid theoretical foundation to guide the practical realization of the study process.

Then, we juxtaposed the four sessions in Fig. 1 with the basic elements of Table 1 and asked: What type of student

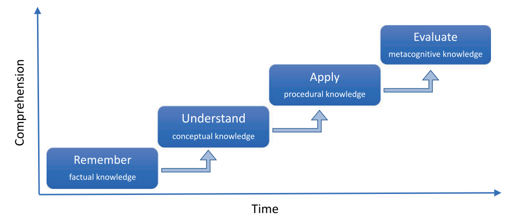

Fig. 1 Organizing the study process into four successive sessions of increasing level of comprehension, according to Bloom's revised taxonomy in knowledge dimension

activities the sessions should include? Which basic elements would aptly support those activities? Which activities benefit from interaction with peers? For example, since the first session focuses on factual knowledge, it should include reading and absorbing new material, which can be done alone. The relevant basic elements should then include technology enhancement (videos and simulations in technology-enhanced learning [TEL] environment), focus on phenomena and concepts (supported by material), alternative conceptions (addressed in the material), and adaptability (personal time and tempo). After considering the other three sessions the same way, we devised a timeline for the study process, with basic elements included (Table 2).

Practical realization of the four-step study process

Now we had a solid theoretical foundation and a generic four-step process (Table 2) that we could transform into a practical realization, the primetime learning model (Table 3). For clarity, we also relabeled the four steps as (i) principles, (ii) practice, (iii) problems, and (iv) primetime (Fig. 2).

Step 1. Principles: self-studying of the topic

In the first step, students use videos and a textbook to study the principles and central concepts by themselves. The emphasis is on learning the basics, on remembering the factual knowledge, and on forming an overall picture of the topic. This step is akin to the self-studying in flipped classroom (Mazur 1997). Videos give an overview, and textbooks expand the topic by examples and further details. Self-studying is assessed in the end by a test in TEL environment, which gives immediate feedback. The test aims to motivate the students to familiarize themselves with the facts and principles applied in the following steps. The instructor assembles instructional materials for study but has minimal direct interaction with students during this step.

Step 2. Practice: groups apply the principles

After studying the principles, the groups meet—*whenever they want, wherever they want, and without the teacher*—to put principles into practice. The emphasis is on conceptual understanding and on uprooting alternative conceptions. The group does this by completing a research-based set of assignments in the TEL environment. The assignments include visualizations, PhET and other simulations (Wieman et al. 2008), numerical problems, and context-rich, scaffolded problem-solving (Heller and Hollabaugh 1992; Kapur et al. 2008; Maloney 2011). Optimally, the assignments are open and support inquiry-based learning processes, which are known to increase both learning gains and interest in science (Pedaste et al. 2015; Raes et al. 2014). Conceptual questions, familiar from peer instruction lectures, are suitable as they are designed to address alternative conceptions and generate vivid discussions (Beatty et al. 2006).

The answers to the questions are part of the assessment and give points to group members present in the meeting, which encourages the members to collaborate and to secure answers by proper arguments (Smith et al. 2009). Small group sizes help to lower the barrier to express opinions. This organization creates positive interdependence among group members (Heller et al. 1992). After answering the assignments, the TEL environment offers correct answers and correct arguments immediately, as advised by earlier research (Dihoff et al. 2004).

The meetings are flexible, and groups can make them suit their taste. Tempo is determined by the groups' interests, and because of the smallness of the groups, students

Table 2 Sketch for a four-step study process. Here, the elements of active learning from Table 1 are identified and assigned to the study process of Fig. 1

Knowledge dimension	Cognitive process	Active elements (from Table 1)	Example activities and notes
Factual	Remember	Te, Al, Ph, Co, Fo, Re, Ad	Expositions, books, videos. Can be done alone. The principal active element is technology enhancement.
Conceptual	Understand	In, Te, Al, Ph, Co, Se, Fo, Re, Ad	Uproot alternative conceptions and ensure correct understanding. Work through questions. The principal active element is interaction with peers.
Procedural	Apply, analyze	Pr, Te, Al, Ph, Co, Re, Ad	Problem-solving. Concepts in real life. Calculations. The principal active element is problem-solving skills.
Metacognitive	Analyze, evaluate	In, Al, Ph, Co, Se, Fo, Ad	Reflect, face mistakes, look back. The teacher has a prominent role. The principal active elements are interaction, feedback, and formative assessment.

Table 3 The four-step study process of the primetime learning model. The process represents a practical realization of the sketch in Table 2

Step	Activity	Realization	Assessment and feedback
Principles (factual knowledge)	Study the topic alone.	Watch videos and read a book. Can be done anytime, but preferably well before the next step.	Test in TEL environment. Immediate feedback (correct answers and points).
Practice (conceptual knowledge)	Group meets to practice using the principles and concepts.	Assignments in TEL environment: conceptual questions, simulations, numerical exercises, short problems, and reflective assignments that support collaborative inquiry-based learning. Group can meet anytime and anywhere. The teacher is not present.	TEL environment offers immediate feedback (correct answers and points; group members present in the meeting share the same points).
Problems (procedural knowledge)	Apply the concepts in full-scale problem-solving.	Solve physics problems alone or collaboratively. Reinforce explicit problem-solving skills. Teacher support available when needed. Solutions (e.g., scanned papers) are submitted to TEL environment by a deadline.	After deadline, TEL environment reveals correct solutions. Students grade and correct their solutions based on given criteria. Teacher verifies corrections and gives feedback.
Primetime (metacognitive knowledge)	Students and the group receive personal support from the teacher.	Group meets teacher privately to discuss remaining problems and to reflect upon learning difficulties.	Teacher gives oral feedback for the group and each student personally.

have better chances to address individual needs. Although the teacher is absent, TEL environments can adopt some of the teacher's routine work (Bell et al. 2010; Maloney 2011; Wagh et al. 2017). Precious contact time with teachers, as discussed later, will increase in later steps of the study process.

Principles and practices can also repeat twice before proceeding to the following steps. Such an arrangement helps to balance study load and to lessen the amount of material per session.

Step 3. Problems: Full-scale problem-solving

After the principles are known and rehearsed under the guidance of TEL environment, students proceed to solve full-scale problems, as familiar from traditional course designs. The emphasis is on procedural understanding, on analyzing realistic, context-rich problems, and on applying the concepts in realistic settings. Problems may be adopted from textbooks, but they should explicitly teach problem-solving skills and go beyond mere symbol manipulation. The problems can also be based on the

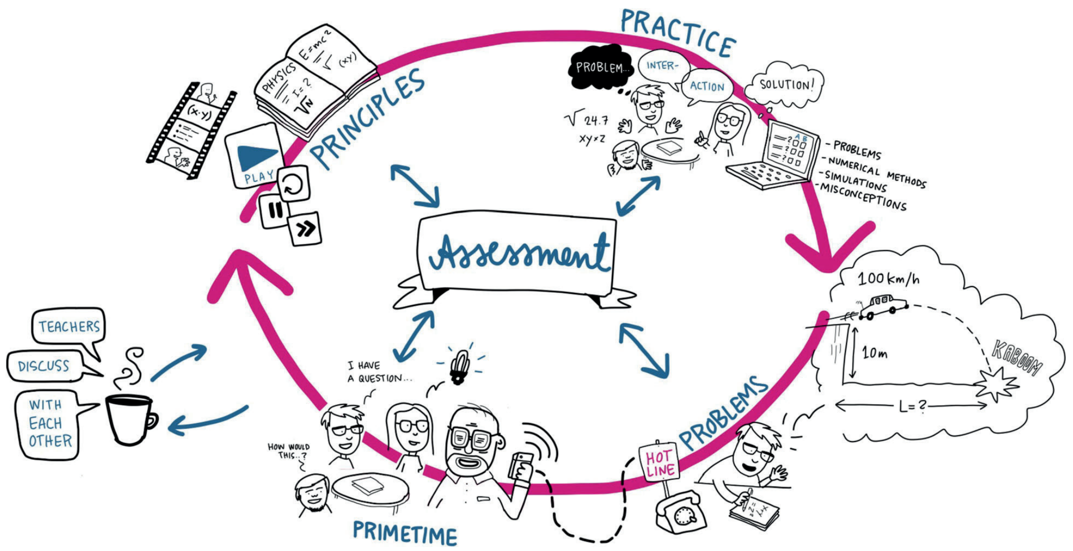

Fig. 2 Primetime learning model with the four-step study process: principles, practice, problems, and primetime. Formative assessment underlies the entire process and motivates students to perform activities that also directly affect the grade. This drawing is a succinct summary of the primetime model (drawing courtesy of Linda Saukko-Rauta)

simulations and numerical assignments used during practice sessions. For help and guidance, the teacher needs to be available for the students via a hotline. The hotline means quick, precise answers for precise questions which takes only little time from the teacher. Hotline can be arranged as scheduled availability, most easily in an online chat (Fig. 2).

Students submit personal solutions in the TEL environment by a given deadline. An easy realization is to upload scanned or photographed hand-written solutions. Model solutions are published *immediately* after the deadline (Dihoff et al. 2004). Assessment is designed such that students are made to face their mistakes by letting them check and correct their solutions, grade them based on given criteria and reupload the graded and corrected solutions in the TEL environment. In return, students get weekly feedback and brief, specific suggestions to enhance self-assessment and problem-solving skills. In other words, following research-based guidelines, students reflect upon open questions and receive immediate feedback about their successes and mistakes. The feedback is invaluable for the preparation for the next step: primetime.

Step 4. Primetime: quality time between group and the teacher

In the fourth and final step, the group has a *private meeting with the teacher*, the primetime meeting. By now students have already studied, practiced, and reflected on their skills so the hope is that only the most urging conceptual challenges remain to be resolved at this meeting. The subtleties of the difficult material can be worked through during a face-to-face dialog with the teacher. The step focuses on productive teacher-student interaction (Furberg 2016). This focusing enables the precious time of the teacher to be used effectively. The emphasis is therefore not on correct answers—for they are already known—but on remaining questions and challenges and on metacognitive knowledge. In other words, the teacher is at group's disposal, and the group can take advantage of this time as it deems appropriate. For example, the group can also ask questions about following week's new problems. The content is chosen by the group, not by the teacher. This opportunity urges the group to use the time well.

Yet the most auspicious aspect of primetime lies beyond physics, in the strong interaction and personal contact. Primetime is quality time between the group and the teacher, where quality refers to a genuine presence, meetings at an intimate level, attending to individual problems, knowing every student's name and character, strengthening grouping, and conveying a message that the teacher cares about the students (Schoeberlein 2009). This interaction supports students' social and academic integration, enhances their feeling of belonging, and thereby has the potential to contribute positively to student retention (Aguilar et al. 2014; Wilcox et al. 2005). Personal contact can also prevent coasting because it enables doing useful "checking" of each student. A homely atmosphere can be promoted by having primetimes in the same, informal study areas as the group meetings or, say, even at cafés around the campus area.

Primetime then completes the study process, and the students begin the same process with a new topic.

The role of a teacher is twofold

On the one hand, thanks to personal interaction in primetime, teachers are visible mentors and coaches, real individuals that answer questions, provide guidance, and offer students genuine presence (Jennings and Greenberg 2009; Sharp and Jennings 2016). On the other hand, teachers are invisible facilitators who enable efficient studying. At the beginning of the course, they offer schedules, study environments, and opportunities for social support. During the course, they offer materials, assignments, and online help for problem-solving. Only primetimes are scheduled by teachers; other sessions are planned and run by students. Students are in charge of the study process at all times.

Assessment powers the process

Since the process relies on independent student and group work, strategic support from the formative assessment is essential (Figs. 2 and 3). Cauley and McMillan noted that "formative assessment provides valuable information for both students and teachers" and "feedback and instructional correctives can be a powerful technique to support student motivations and achievement" (2017). Consequently, here, the purpose of assessment is not merely to grade students' knowledge and skills, but to support and empower the study process itself to guide teachers to steer the study process and to respond to students' difficulties (Bennett and Bennett 2017; Black et al. 2017; McManus 2008). In particular, the continuous nature of learning is best emphasized by a continuous nature of assessment (Rohrer and Pashler 2010). Because a summative exam at the end of the course would have broken these principles, it was not included in the assessment. Instead, we integrated the assessment with the model to leave minimal distinction between assessment and the study process itself.

Students accumulate points from several sources. The total number of points determines the grade and at least half of the maximum points are required for passing (Fig. 3). Most points accumulate during the course from principles, practice, and problems. Points for principles and practice come from TEL environment automatically, and points for problems come from students' grading (verified by the teacher). Points from principles are used to motivate self-studying before group meetings, and points from practice are used to encourage students into productive group meetings. This setting supports both

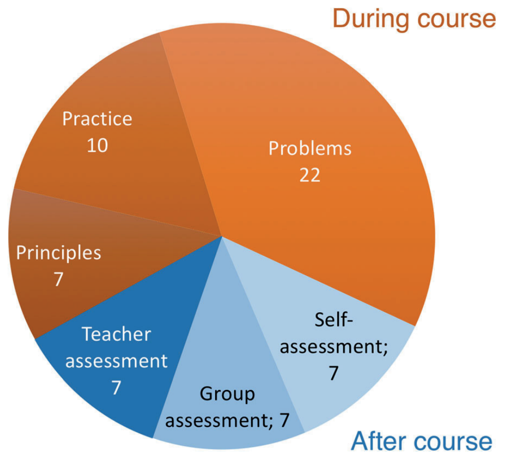

Fig. 3 The composition of points in the grading. Points from practice, principles, and problems accumulate during the course, and points from self-, group, and teacher assessments are given at the end of the course. The maximum number of points is 60, and passing requires half of these points. The exact composition of points can be adjusted, but this is our fair estimate for a balanced compromise, where passing the course is straightforward by abiding and persistent studying and difficult by random or cherry-pick studying. Near-fail students can, if necessary, be allowed to pass the course by compensating work (Arnold 2016)

individual accountability and positive interdependence (Knight 2004b).

At the end of the course, the accumulated points are complemented by criteria-based self-, group, and teacher assessments. Self-assessment aims to support skills in self-reflection and metacognition (Boyd 1995; McMillan and Hearn 2008). Allowing the students' views on own learning to influence the grade has been shown to improve motivation (McMillan and Hearn 2008). Group assessment aims to inhibit coasting and to teach cooperative learning (Joyce 1999). Each member gives the group points and verbal assessment, and all the group members share the median of individual points. The assessment criteria concern only the group and its functioning, which support the perception of positive interdependence (Johnson and Johnson 1999). Note that the majority (72%) of the points still comes from individual work and a minority (28%) from group-related work. The assessment thus represents a fair balance between individual content mastery and group activities, especially given the method's versatile learning goals, one of which is specifically the learning of collaborative skills.

At the same time, students also give verbal peer feedback, which however is for teachers' eyes only. Teachers analyze this feedback to ensure constructive tone, add own evaluation of student performance based on primetime meetings, and compose focused, constructive, and personal feedback for each student. At the end of the course, each student thus receives constructive verbal feedback that provides insights into course performance beyond a mere grade. Such focused interventions have been shown to trigger far-reaching positive consequences (Aguilar et al. 2014).

Comments on student groups and the learning environment

Formal group training is useful but not necessary. While the method does put responsibility on the students and groups, the group activities are well structured and provide a safe learning environment even for the inexperienced students. After all, one of the goals of this method is the very learning of collaborative skills themselves, which takes years to learn anyway.

Optimal group composition and size are difficult questions (Harlow et al. 2016; Heller et al. 1992; Jensen and Lawson 2011), and the best choices likely depend heavily on the context. Regarding composition, Heller and Hollabaugh (1992) recommend groups of students with heterogeneous academics. We chose to group students homogenously according to how much effort they wanted to put in the course, with the hope that this homogeneity would prevent coasting. However, the conclusions on group compositions are often contradictory, so other instructors interested in using this strategy should consider grouping criteria that would best fit their contexts and institutional settings.

Choosing an appropriate group size is important for promoting productive active learning (Freeman et al. 2014). We chose a group of around four to five students so there is a diversity of ideas, but the group is small enough that every student should contribute, to minimize loafing. This size can even be considered large (Heller and Hollabaugh 1992), but it makes groups tolerate occasional and inevitable non-attendances during the course. Group size is also affected by teacher resources. By assuming that each group requires about 1 h of contact time each week, each student takes about 10–15 min of weekly contact time from one teacher. In contact teaching, teachers and teaching assistants are considered equal; for us, they are all "teachers."

Regarding learning environment, note that the model needs no auditoriums or classrooms with specialized equipment. The only physical requirements are study areas for the group activities; the ideal environments are informal, lobby-type areas. The model only requires a suitable technology-enhanced learning (TEL) environment. The TEL environment should be able to integrate videos, simulations, queries, interactive elements, and numerical codes, preferably all in one place because full integration gives better control over the student's workflow. The environment should be able to provide a detailed log data of student activities. Access to the TEL environment requires computers, but students' laptops suffice well (students' computers at home and one laptop per group in group meetings).

Methods and materials

The primetime learning model was piloted in 2016 and 2017 on a 7-week second-year university physics course on thermodynamics and optics. The courses had 72 (2016; 25% female) and 77 (2017; 31% female) active students (both physics majors and minors) that were divided into groups of five students (14 groups in both courses). In both pilots, the groups were formed by the teacher. In 2016, groups were made homogeneous concerning the importance the students gave to the course, and in 2017, they were made based on scheduling so that each student would weekly have a maximum amount of common time available with the other group members (according to pre-course questionnaires). The courses had three teachers, consisting of one faculty member responsible for the course and two teaching assistants, one graduate and the other undergraduate student. TEL environment was The Interactive Material (TIM) (Lappalainen 2015).

The pilot courses in 2016 and 2017 are compared with the courses in 2014 and 2015. The 2014 and 2015 courses had the same content, the same teachers (except for a different undergraduate student), and a similar number of active students (97 in 2014 and 72 in 2015) with a similar gender and demographic characteristics. The only difference was the teaching method, which consisted of typical flipped classroom setting: First, self-studying from book and videos was assumed before lectures (Knight 2004a). Second, lecture time was used not for lecturing but for demonstrations and peer instruction, which consisted of students typically answering multiple-choice questions alone and after discussion with peers, following the practice made popular by Mazur (Mazur 1997). There was no lecturing. Third, lectures were followed by problem-solving and recitation classes. And fourth, the course ended with a summative exam. The maximum number of points was 60, with two points obtained from self-study tests, 12 points from problem-solving, and the remaining 46 points from an end-of-course summative exam.

To answer the first research question about student activity, we measured the number of submitted solutions in the practice phase; an equivalent measure could be used for all four courses (2014–2017). The activities and study habits of groups and individual students were analyzed using the TEL environment log data (timestamps and points for the submission of each answer in each step of the process).

To answer the second research question about assessment, we analyzed the assessment from several viewpoints. First, we compared how the distribution of the points in total varied between the years 2014 and 2017 and between different assessment criteria. Second, relating to the primetime learning model, we studied how the points from principles, practice, and problems correlated with the self-assessment points and how teacher and group assessment points are compared to self-assessment points. Third, the functioning of assessment was explored by the analysis of student's learning outcomes using pre- and posttests on thermodynamics concepts. The pretests took place during introductory lectures and posttest a couple of weeks after finishing the section on thermodynamics. The test in 2016 was modified from an earlier study (Leinonen et al. 2013). It involved heat transfer and maximum work related to cyclic and non-cyclic processes containing isochoric, isobaric, and isothermal basic processes. The test in 2017 was Thermodynamic Concept Survey (TCS) adopted from an earlier study (Wattanakasiwich et al. 2013). It was translated from English to Finnish but otherwise given as guided by the developers. Thus, the tests in 2016 and 2017 were different, and gains are not comparable; preliminary results in this article will be systematized by further dedicated studies. The tests did not affect students' grades but were quantified for each student using Hake's normalized gains, defined as $g = (post - pre)/(1 - pre)$, where the *pre* and *post* are the percentages of correct answers (Hake 1998).

To answer the third research question about the learning experience, student opinions were quantified by end-of-course questionnaires (data only from 2016). Students' experiences about group meetings and about working without a teacher were queried by open feedback questionnaires at the end of each practice session. Student experiences were also monitored routinely by face-to-face dialogs during primetime. Experiences and possible occurrences of coasting were explored during primetime discussions and monitored by spotting anomalies in TEL log data.

Results

Research question 1: students followed the process rigorously

The model was able to improve retention and prolong student activity (Fig. 4a). During earlier years, despite the particular basic elements of active learning, student activity declined considerably during the course. A common perception for the cause of this decline is that students start to wait for the exam. Here, the improved retention may have several origins: social integration, formative assessment, or the structured study process that supported balanced study habits.

The prolonged activity can also be understood in the light of study rhythm. Students acquired rapidly a steady study rhythm, which remained stable throughout the course (Fig. 4b). Principles preceded practice systematically, presumably due to encouragement from assessment. Most groups had practice during specific times, but some groups exploited their freedom to meet during more

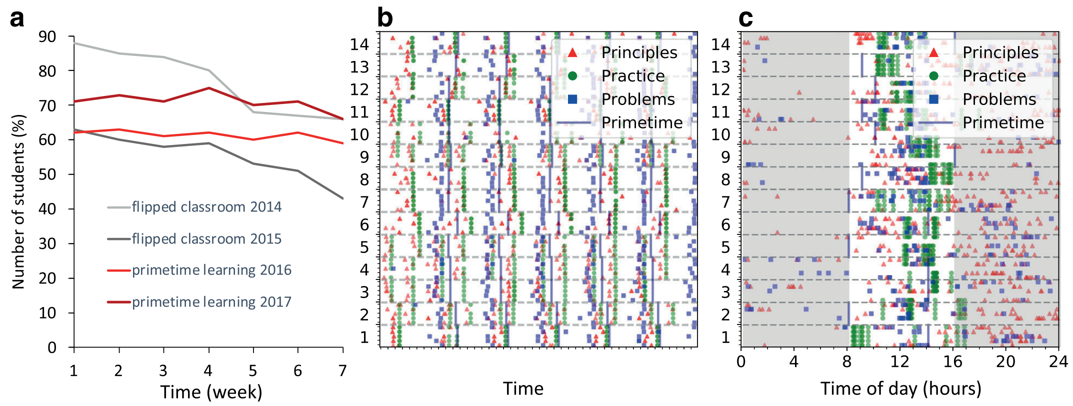

Fig. 4 Analysis of TEL environment log data. **a** The number of active students in the course plotted using the number of students who actively solved problems. **b** Timestamps for principles (red triangles), practice (green circles), problem answer submissions (blue squares), and primetimes (vertical lines) for each student as a function of time. Groups are numbered and separated by horizontal dashed lines. Data are shown only for 2016; data for 2017 are similar. **c** The data of the panel **b** compressed to 1 day and night. Shaded areas indicate the time of day outside 8 am and 4 pm

unconventional times. In overall, white regions in Fig. 4b are absent, and the distribution of symbols is similar across different groups and throughout the courses. Students thus followed the study process rigorously and well accordingly to the intended schematic of Fig. 2.

Group meetings took place mostly between 9 am and 6 pm, and practices and problem submissions took place evenly from 9 am until late midnight (Fig. 4c). Some students worked throughout the night. The deadline for the submission of problem solutions was at 2 pm on Mondays, but submissions took place also at other times. In other words, students worked whenever suitable and not just before deadlines, which helped to level the workload.

In sum, the primetime learning model indeed appeared capable of improving and prolonging student activity, at least when compared with the earlier flipped classroom approach.

Research question 2: assessment was robust and functional

The main purpose of the assessment in the primetime model was to support the study process. However, since the assessment did not contain a final exam, it still had to warrant legitimate grading and reasonable criteria for passing. Despite the lack of exams in 2016 and 2017, the total point distribution was qualitatively similar to the mainly summative assessment from previous years. However, there were two notable differences (Fig. 5a). First, the failure rate decreased. The failure rate of students with some course activity decreased from 10% (in 2014) and 15% (in 2015) down to 6% (in 2016) and 5% (in 2017). Preliminary analysis of differences in gender shows that male students benefited from this model more than female students, especially because in 2014 and 2015, the low-performing students were mostly male. Second, and most important, the majority of the failed students in the pilot course scored zero points—they had enrolled in the course but never even started studying.

Based on earlier research on different aspects of assessment (Brown et al. 1997), the assessment here seemed reliable. Students did not cherry-pick just the easy parts but were active in the entire study process. Self-assessment correlated well with the sum of points from principles, practice, and problems ($p \ll 0.001$; Fig. 5b). The good correlation suggests a valid assessment and implies that study efforts during the course got reflected in the self-assessment. On average, the percentage of points from self-assessment was smaller than the percentage of summed points from principles, practice, and problems. Thus, if anything, students were inclined to be more self-critical than self-generous. Self-assessments correlated even with teacher assessments (Fig. 5c), despite somewhat different criteria.

Correlations between self- and group assessments show an intriguing trend: students always valued their groups high (Fig. 5c). The criteria for the group and self-assessments were different, so the assessments did not even need to correlate well. Nevertheless, it is remarkable how students valued groups high *regardless* of their own perceived performance.

The low failure rate and the reliability of the assessment are consistent with good learning outcomes (Fig. 6). We quantified the outcomes using Hake's normalized gains,

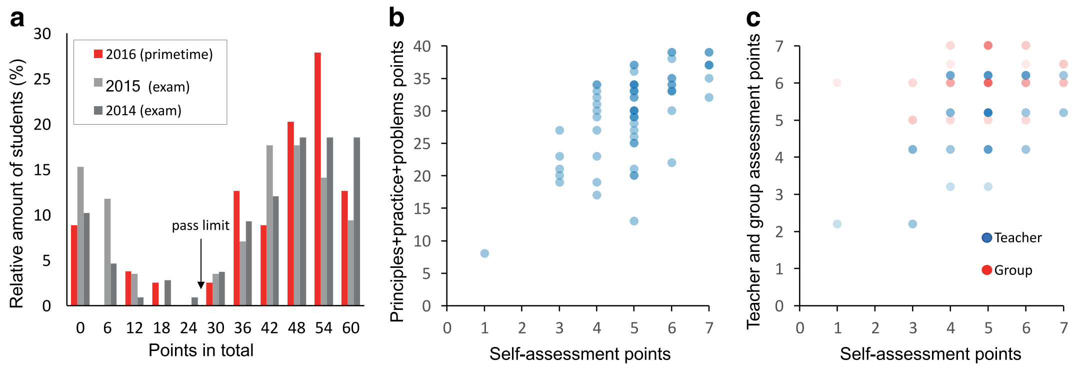

Fig. 5 Analysis of the points in assessment. **a** The normalized distribution of total points. The pilot course is compared with two courses taught in earlier years using flipped classroom and assessed mainly by a final exam ($N_{2014} = 108$, and $N_{2015} = 85$, $N_{2016} = 79$, $N_{2017} = 82$). The pass limit is 30 points. **b** Correlation between points from self-assessment and the sum of points from principles, practice, and problems. **c** Correlation between self- and teacher assessment and self- and group assessment points. In **b** and **c**, color intensity is proportional to the frequency of occurrence. In **c**, teacher and group assessment symbols are slightly offset for clarity

which were $g = 0.63$ (SD 0.33) in 2016 and $g = 0.33$ (SD = 0.20) in 2017. Although room for improvement exists, these gains represent decent learning outcomes (Hake 1998).

Research question 3: model gave a positive learning experience

The model improved retention, leveled workload, and decreased failure rates (Figs. 4 and 5). Also, the feedback from practice sessions showed that technology-enhanced learning sessions without a teacher could surpass common interactive lectures in intensity, effectiveness, and interaction strength. In certain occasions, scaffolding by the teacher or by TEL environment would have been beneficial. However, even without teacher presence, the groups did not experience coasting as a problem.

Although only about one third of the students ended up answering the end-of-course questionnaires, the echo from the feedback had the same tone as during the course: students considered the model clear (94% agreed or agreed partly to a related claim) and functional (89%) and the workload legitimate (89%). The assessment was considered unambiguous (86%), encouraging (90%), and less stressful than exams (81%). Most of the criticism, more visible in open feedback, was related to problems in scheduling and technical issues. In particular, many students were disoriented and baffled by the lack of lectures and by the absence of an exam. Presumably, the bafflement arose mostly due to environmental factors, reflecting the deep roots that lectures and exams have in our teaching culture (Dori et al. 2007), because the feedback was otherwise positive.

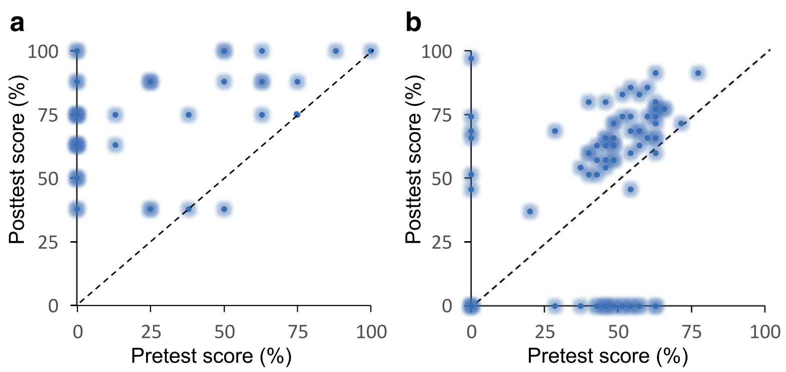

Fig. 6 Pre- and posttest scores in **a** 2016 ($N_{pre} = 59$, $N_{post} = 49$) and **b** 2017 ($N_{pre} = 67$, $N_{post} = 56$). The intensity of each point is proportional to the number of students with the given scores. Note that the tests in **a** and **b** were different

Finally, students claimed the primetime model promoted new friendship (85%), appropriate responsibility of one's studies (100%), and groups that provided a sense of belonging (100%). Thus, the model supported social integration.

In the open feedback, on the one hand, the new study routines and the lack of exam were criticized: "I learn better from standard lectures" and "…while it's nice not to have an exam, it would be good to have 'a real indicator' to measure what you learned." On the other hand, despite the new routines, most of the students considered the model valuable: "This model is a true fulfilment of peer instruction and peer discussions," "The small group helps to realize that someone really cares and is present", and "[Primetime teacher's] presence and the ability to ask questions that occupy one's mind was an excellent thing!" Students also valued learning skills beyond physics: "[The model] also taught working life skills" and "This course will be remembered just because of the group."

Discussion and conclusions

To clarify the institutional context, the pilot institute accepts 40–60 new physics major students, one quarter to one third of them female, practically all of them Finnish students in their early 20s. Most of these majors receive BSc in 3 years, followed by an MSc degree in an additional couple of years, with emphasis on material physics, nuclear physics, particle physics, or cosmology. The teaching language for courses at the bachelor level is Finnish, and most course participants are full-time students. The courses are usually taught by one faculty member and few teaching assistants (one assistant per 20–30 students) and the contact hours (without preparation time) are typically around 4 to 6 h per week per teacher. The instructional workload of the method was approximately on a par with the workload of more conventional teaching methods.

The model naturally has its challenges, even if cultural and institutional contexts determine their relative priority. First, some students prefer studying alone and dislike group work. However, here, the group activities are well-structured and thereby provide a secure and natural way to learn collaborative skills, which anyway should be a part of any modern science curriculum. Second, teaching assistants need to be skilled, as they alone are responsible for instructing and assessing their groups. Skills are required in both subject matter and pedagogy, especially regarding the caveats and intricacies of group dynamics (Feldon et al. 2011). Teachers must feel at ease with the spontaneity and unexpectedness of primetime meetings; after all, only the most difficult problems filter to the teacher. Teachers must be sensitive to the atmosphere in each group and, if necessary, to keep groups functional and react with timely interventions. Third, the primetime model is transformational compared with traditional course designs. Active lectures cannot be gradually migrated into the primetime model; the model requires a complete renovation of existing practices. And fourth, succesful studying requires learners to self-regulate their learning (Littlejohn et al. 2016). Zimmermann and Schunk (2012) define self-regulation as self-generated thoughts, feelings, and actions planned and cyclically adapted based on performance feedback to attain self-set goals. Self-regulated learners actively construct knowledge and use cognitive and metacognitive strategies to regulate their learning. It is argued that all learners use regulatory processes to some degree, and therefore, our future aim is to investigate self-regulation processes in the primetime learning context.

At the same time, however, the transformational nature supports the adoption of research-based instructional strategies. The model sets students in charge of their learning process, so the studying in this model—by its very construction—is less susceptible to teachers' opinions or attitudes. After all, "active teaching" with unfit attitudes can be worse than good passive lecturing (Andrews et al. 2011).

The potential for enhanced adoption of research-based instructional strategies is also supported by teacher experiences. Both in 2016 and 2017, the teachers in the courses met weekly to share experiences and observations. All teachers, four in total, experienced primetime meetings pleasurable and empowering. Despite the large-enrollment classes, teachers learned students by name and character, and this personal contact made teaching feel meaningful and genuine. (From student's perspective: each student knew own teacher personally.) For teachers, the pilot courses were arduous, but mainly because of novelty. In the long run, depending on class size, teacher workload ought to remain on par with flipped classroom approach—thanks to the focused contact time in the primetime meetings.

Moreover, the model comes with subsidiary benefits. It is affordable for the teacher and the institute. It can be scaled to small and large classes alike. It promotes equality by providing all the students with a similar social environment. It makes student minorities less pronounced, as studying in small groups foster a stronger sense of belonging (Aguilar et al. 2014; Madsen et al. 2013). Due to the interactive, collaborative, and structured nature of the learning process, it suits particularly well for courses that focus on teaching balanced study habits and strengthening social integration. Such courses are opportune for teaching young students group work, systematic study habits, and tools for improving metacognitive skills.

To conclude, the model is also flexible. The four steps are built on a solid theoretical foundation and therefore represent a generic framework that can easily be developed further. Consequently, our objective is to pursue the research-based development of student activities, interactions, and assignments. In particular, the primetime learning model is not specific to university physics or even other STEM subjects; it is applicable to many subjects and levels of study.

Abbreviations
TCS: Thermodynamic Concept Survey; TEL: Technology-enhanced learning; TIM: The interactive material

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Availability of data and materials
Please contact the corresponding author for data and materials.

Authors' contributions
PK conceived the model and developed it further with JM and JL. PK conducted the pilots, assisted by JL. All contributed to developing the theory, and all authors contributed to and approved the final manuscript.

Ethics approval and consent to participate
Procedures followed were in accordance with the ethical standards of the University of Jyväskylä. Students' written consent to participate in the study was obtained. Analysis and presentation of data preserved the anonymity of participants.

Competing interests
The authors declare that they have no competing interests.

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References
Aguilar, L, Walton, G, Wieman, C. (2014). Psychological insights for improved physics teaching. *Physics Today*, *67*(5), 43–49. https://doi.org/10.1063/PT.3.2383.

Anderson, LW, & Krathwohl, DR (Eds.) (2001). *A taxonomy for learning, teaching, and assessing: A revision of Bloom's taxonomy of educational objectives, abridged edition*. New York: Pearson.

Andrews, TM, Leonard, MJ, Colgrove, CA, Kalinowski, ST. (2011). Active learning not associated with student learning in a random sample of college biology courses. *CBE Life Sciences Education*, *10*(4), 394–405. https://doi.org/10.1187/cbe.11-07-0061.

Arnold, I. (2016). Resitting or compensating a failed examination: Does it affect subsequent results? *Assessment & Evaluation in Higher Education*, *2938*(October), 1–15. https://doi.org/10.1080/02602938.2016.1233520.

Beatty, ID, & Gerace, WJ. (2009). Technology-enhanced formative assessment: A research-based pedagogy for teaching science with classroom response technology. *Journal of Science Education and Technology*, *18*(2), 146–162. https://doi.org/10.1007/s10956-008-9140-4.

Beatty, ID, Gerace, WJ, Leonard, WJ, Dufresne, RJ. (2006). Designing effective questions for classroom response system teaching. *American Journal of Physics*, *74*(1), 31. https://doi.org/10.1119/1.2121753.

Beichner, RJ, Saul, JM, Abbott, DS, Morse, JJ, Deardorff, D, Allain, RJ, et al. (2007). The Student-Centered Activities for Large Enrollment Undergraduate Programs (SCALE-UP) project abstract. *Physics*, *1*(1), 1–42 http://www.percentral.com/PER/per_reviews/media/volume1/SCALE-UP-2007.pdf.

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. https://doi.org/10.1080/09500690802582241.

Bennett, RE, & Bennett, RE. (2017). Formative assessment: A critical review. *Assessment in Education: Principles, Policy & Practice*, *18*(1), 5. https://doi.org/10.1080/0969594X.2010.513678.

Black, P, Wiliam, D, Black, P, Wiliam, D. (2017). Assessment and classroom learning. *Assessment in Education: Principles, Policy & Practice*, *5*(1), 7. https://doi.org/10.1080/0969595980050102.

Boyd, D (1995). *Enhancing learning through self-assessment*. London: RoutledgeFalmer.

Brown, G, Bull, J, Pendelbury, M (1997). *Assessing student learning in higher education*. London: Routledge.

Burgan, M. (2006). In defense of lecturing. *Change*, *6*, 31 https://www.tandfonline.com/doi/abs/10.3200/CHNG.38.6.30-34.

Cauley, KM, & Mcmillan, JH. (2017). Formative assessment techniques to support student motivation and achievement. *The Clearing House*, *83*, 1. https://doi.org/10.1080/00098650903267784.

Crouch, CH, & Mazur, E. (2001). Peer instruction: Ten years of experience and results. *American Journal of Physics*, *69*(9), 970. https://doi.org/10.1119/1.1374249.

De Jong, T, & Njoo, M. (1992). Learning and instruction with computer simulations: Learning processes involved. *Computer-Based Learning Environments and Problem Solving*, *84*, 411–427 https://research.utwente.nl/en/publications/learning-and-instruction-with-computer-simulations-learning-proce.

Deslauriers, L, Schelew, E, Wieman, C. (2011). Improved learning in a large-enrollment physics class. *Science*, *332*, 862.

Dihoff, R, Brosvic, GM, Epstein, ML, Cook, MJ. (2004). Provision of feedback during preparation for academic testing: Learning is enhanced by immediate but not delayed feedback. *The Psychological Record*, *54*(2), 207–231 http://opensiuc.lib.siu.edu/tpr/vol54/iss2/4/.

Dori, YJ, Hult, E, Breslow, L, Belcher, JW. (2007). How much have they retained? Making unseen concepts seen in a freshman electromagnetism course at MIT. *Journal of Science Education and Technology*, *16*(4), 299–323. https://doi.org/10.1007/s10956-007-9051-9.

Dufresne, RJ, & Gerace, WJ. (2004). Assessing-to-learn: Formative assessment in physics instruction. *The Physics Teacher*, *42*(7), 428–433. https://doi.org/10.1119/1.1804662.

Enghag, M, Gustafsson, P, Jonsson, G. (2009). Talking physics during small-group work with context-rich problems—analysed from an ownership perspective. *International Journal of Science and Mathematics Education*, *7*(3), 455–472. https://doi.org/10.1007/s10763-008-9125-z.

Feldon, DF, Peugh, J, Timmerman, BE, Maher, M a, Hurst, M, Strickland, D, et al. (2011). Graduate students' teaching experiences improve their methodological research skills. *Science (New York, N.Y.)*, *333*(6045), 1037–1039. https://doi.org/10.1126/science.1204109.

Freeman, S, Eddy, SL, McDonough, M, Smith, MK, Okoroafor, N, Jordt, H, Wenderoth, MP. (2014). Active learning increases student performance in science, engineering, and mathematics. *Proceedings of the National Academy of Sciences of the United States of America*, *111*(23), 8410–8415. https://doi.org/10.1073/pnas.1319030111.

Furberg, A. (2016). Teacher support in computer-supported lab work: Bridging the gap between lab experiments and students' conceptual understanding. *International Journal of Computer-Supported Collaborative Learning*, *11*(1), 89–113. https://doi.org/10.1007/s11412-016-9229-3.

Hake, RR. (1998). Interactive-engagement versus traditional methods: A six-thousand-student survey of mechanics test data for introductory physics course. *American Journal of Physics*, *66*, 64.

Halloun, IA, & Hestenes, D. (1987). Modeling instruction in mechanics. *American Journal of Physics*, *55*(August 1984), 455. https://doi.org/10.1119/1.15130.

Harlow, JJB, Harrison, DM, Meyertholen, A. (2016). Effective student teams for collaborative learning in an introductory university physics course. *Physical Review Physics Education Research*, *12*(1), 10138. https://doi.org/10.1103/PhysRevPhysEducRes.12.010138.

Hattie, J, & Timperley, H. (2007). The power of feedback. *Review of Educational Research*, *77*, 81. https://doi.org/10.1111/j.1365-2923.2009.03542.x.

Heller, P, & Heller, K (1999). *Cooperative group problem solving in physics*. Minnesota: University of Minnesota.

Heller, P, & Hollabaugh, M. (1992). Teaching problem solving through cooperative grouping. Part 2: Designing problems and structuring groups. *American Journal of Physics*, *60*(7), 637–644. https://doi.org/10.1119/1.17118.

Heller, P, Keith, R, Scott, A. (1992). Teaching problem solving through cooperative grouping. Part 1: Group versus individual problem solving. *American Journal of Physics*. https://doi.org/10.1119/1.17117.

Henderson, C, Dancy, M, Niewiadomska-Bugaj, M. (2012). Use of research-based instructional strategies in introductory physics: Where do faculty leave the

innovation-decision process? *Physical Review Special Topics - Physics Education Research*, *8*(2), 1–15. https://doi.org/10.1103/PhysRevSTPER.8.020104.
Herrmann, KJ. (2013). The impact of cooperative learning on student engagement: Results from an intervention. *Active Learning in Higher Education*, *14*(3), 175–187. https://doi.org/10.1177/1469787413498035.
Hestenes, D. (1987). Toward a modeling theory of physics instruction. *American Journal of Physics*, *55*(5), 440–454. https://doi.org/10.1119/1.15129.
James, MC, & Willoughby, S. (2011). Listening to student conversations during clicker questions: What you have not heard might surprise you! *American Journal of Physics*, *79*(1), 123–132. https://doi.org/10.1119/1.3488097.
Jennings, PA, & Greenberg, MT. (2009). The prosocial classroom: Teacher social and emotional competence in relation to student and classroom outcomes. *Review of Educational Research*, *79*(1), 491–525. https://doi.org/10.3102/0034654308325693.
Jensen, JL, & Lawson, A. (2011). Effects of collaborative group composition and inquiry instruction on reasoning gains and achievement in undergraduate biology. *CBE Life Sciences Education*, *10*, 64.
Johnson, DW, & Johnson, RT. (1999). Making cooperative learning work. *Theory Into Practice*, *38*(2), 67. https://doi.org/10.1080/00405849909543834.
Joyce, WB. (1999). On the free-rider problem in cooperative on the free-rider problem in cooperative learning. *Journal of Education for Business*, *74*(5), 271. https://doi.org/10.1080/08832329909601696.
Kapur, M, Voiklis, J, Kinzer, CK. (2008). Sensitivities to early exchange in synchronous computer-supported collaborative learning (CSCL) groups. *Computers and Education*, *51*(1), 54–66. https://doi.org/10.1016/j.compedu.2007.04.007.
Knight, R (2004a). *Physics for scientists and engineers: A strategic approach*. San Francisco: Pearson/Addison Wesley.
Knight, RD (2004b). *Five easy lessons*. San Francisco: Addison Wesley.
Krathwohl, DR. (2002). A revision of Bloom's taxonomy: An overview. *Theory Into Practice*, *41*, 212. https://doi.org/10.1207/s15430421tip4104_2.
Kulik, C-LC, Kulik, JA, Bangert-Drowns, RL. (1990). Effectiveness of mastery learning programs: A meta-analysis. *Review of Educational Research*, *60*(2), 265–299. https://doi.org/10.3102/00346543060002265.
Lappalainen, V. (2015). TIM - the incredible material, https://tim.jyu.fi.
Laws, PW. (1991). Calculus-based physics without lectures. *Physics Today*, *44*(12), 24–31. https://doi.org/10.1063/1.881276.
Leinonen, R, Asikainen, MA, Hirvonen, PE. (2013). Overcoming students' misconceptions concerning thermal physics with the aid of hints and peer interaction during a lecture course. *Physical Review Special Topics - Physics Education Research*, *9*(2), 1–22. https://doi.org/10.1103/PhysRevSTPER.9.020112.
Littlejohn, A, Hood, N, Milligan, C, Mustain, P. (2016). Learning in MOOCs: Motivations and self-regulated learning in MOOCs. *Internet and Higher Education*, *29*, 40–48. https://doi.org/10.1016/j.iheduc.2015.12.003.
Madsen, A, McKagan, SB, Sayre, EC. (2013). Gender gap on concept inventories in physics: What is consistent, what is inconsistent, and what factors influence the gap? *Physical Review Special Topics - Physics Education Research*, *9*(2), 1–15. https://doi.org/10.1103/PhysRevSTPER.9.020121.
Maloney, DP. (2011). An overview of physics education research on problem solving. *Getting Started in Physics Education Research*, *2*(1) http://www.per-central.org/items/detail.cfm?ID=11457.
Mazur, E (1997). *Peer instruction: user's manual*. Upper Saddle River: Prentice hall.
McDermott, LC, & Redish, EF. (1999). Resource letter: PER-1: Physics education research. *American Journal of Physics*, *67*(9), 755–767. https://doi.org/10.1119/1.19122.
McDermott, LC, & Shaffer, PS (2002). *Tutorials in introductory physics*. New Jersey: Addison-Wesley.
McManus, S. (2008). Attributes of effective formative assessment.
McMillan, JH, & Hearn, J. (2008). Student self-assessment: The key to stronger student motivation and higher achievement. *Educational Horizons*, *87*(1), 40.
Muller, D a, Bewes, J, Sharma, MD, Reimann, P. (2007). Saying the wrong thing: Improving learning with multimedia by including misconceptions. *Journal of Computer Assisted Learning*, *24*(2), 144–155. https://doi.org/10.1111/j.1365-2729.2007.00248.x.
Novak, GN, Patterson, ET, Gavrin, A, Christian, W (1999). *Just-in-time teaching: Blending active learning and web technology*. Saddle River: Prentice Hall.
Nussbaum, M, Alvarez, C, McFarlane, A, Gomez, F, Claro, S, Radovic, D. (2009). Technology as small group face-to-face collaborative scaffolding. *Computers and Education*, *52*(1), 147–153. https://doi.org/10.1016/j.compedu.2008.07.005.
Pedaste, M, Mäeots, M, Siiman, LA, de Jong, T, van Riesen, SAN, Kamp, ET, et al. (2015). Phases of inquiry-based learning: Definitions and the inquiry cycle. *Educational Research Review*, *14*, 47–61. https://doi.org/10.1016/j.edurev.2015.02.003.
Raes, A, Schellens, T, De Wever, B. (2014). Web-based collaborative inquiry to bridge gaps in secondary science education. *Journal of the Learning Sciences*, *23*(3), 316–347. https://doi.org/10.1080/10508406.2013.836656.
Redish, EF (2003). *Teaching physics with the physics suite*. New York: Wiley.
Rohrer, D, & Pashler, H. (2010). Recent research on human learning challenges conventional instructional strategies. *Educational Researcher*, *39*(5), 406. https://doi.org/10.3102/0013189X10374770.
Salomone, M, & Kling, T. (2017). Required peer-cooperative learning improves retention of STEM majors. *International Journal of STEM Education*, *4*(1), 19. https://doi.org/10.1186/s40594-017-0082-3.
Schmid, RF, Bernard, RM, Borokhovski, E, Tamim, RM, Abrami, PC, Surkes, MA, et al. (2014). The effects of technology use in postsecondary education: A meta-analysis of classroom applications. *Computers and Education*, *72*, 271–291. https://doi.org/10.1016/j.compedu.2013.11.002.
Schoeberlein, D (2009). *Mindful teaching and teaching mindfulness*. Somerville: Wisdom Publications.
Sharp, JE, & Jennings, PA. (2016). Strengthening teacher presence through mindfulness: What educators say about the cultivating awareness and resilience in education (CARE) program. *Mindfulness*, *7*(1), 209–218. https://doi.org/10.1007/s12671-015-0474-8.
Smith, MK, Wood, WB, Adams, WK, Wieman, C, Knight, JK, Guild, N, Su, TT. (2009). Why peer discussion improves student performance on in-class concept questions. *Science (New York, N.Y.)*, *323*(5910), 122. https://doi.org/10.1126/science.1165919.
Snyder, BR (1971). *The hidden curriculum*. Cambridge: MIT Press.
Springer, L, Stanne, ME, Donovan, SS. (1999). Effects of small-group learning on undergraduates in science, mathematics, engineering, and technology: A meta-analysis. *Review of Educational Research*, *69*(1), 21–51. https://doi.org/10.3102/00346543069001021.
Tinto, V. (1975). Dropout from higher education: A theoretical synthesis of recent research. *Review of Educational Research*, *45*(1), 89–125.
Treagust, DT, Duit, R, Fischer, HE (Eds.) (2017). *Multiple representations in physics education*. Cham: Springer.
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. https://doi.org/10.1002/tea.21379.
Waldrop, MM. (2015). The science of teaching science. *Nature*, *523*, 272.
Wattanakasiwich, P, Taleab, P, Sharma, MD, Johnston, ID. (2013). Development and implementation of a conceptual survey in thermodynamics. *International Journal of Innovation in Science and Mathematics Education*, *21*(1), 29–53.
Wells, M, & Hestenes, D. (1995). A modeling method for high school physics instruction. *American Journal of Physics*, *63*, 606. https://doi.org/10.1119/1.17849.
Wieman, C., & Perkins, K. (2005). Transforming physics education. *Physics Today*, (November), *58*(11), 36. https://doi.org/10.1063/1.2155756.
Wieman, C., Perkins, K., Gilbert, S., Benay, F., Kennedy, S., Semsar, K., et al. (2009). An instructors guide to the effective use of personal response systems ("clickers") in teaching.
Wieman, K, Adams, CE, Perkins, K. (2008). Simulations that enhance learning. *Science*, *322*(31 October), 682–683 http://science.sciencemag.org/content/322/5902/682.
Wilcox, P, Winn, S, Fyvie-Gauld, M. (2005). "It was nothing to do with the university, it was just the people": The role of social support in the first-year experience of higher education. *Studies in Higher Education*, *30*(6), 707–722. https://doi.org/10.1080/03075070500340036.
Zimmermann, B. J., & Schunk, D. H. (2012). Self-regulated learning and academic achievement. Springer Science & Business Media.
Zwolak, JP, Dou, R, Williams, EA, Brewe, E. (2017). Students' network integration as a predictor of persistence in introductory physics courses. *Physical Review Physics Education Research*, *13*(1), 10113. https://doi.org/10.1103/PhysRevPhysEducRes.13.010113.

III

VISUALISING THE TEMPORAL ASPECTS OF COLLABORATIVE INQUIRY-BASED LEARING PROCESSES IN TECHNOLOGY-ENHANCED PHYSICS LEARNING

by

Joni Lämsä, Pekka Koskinen, Raija Hämäläinen, & Jouni Viiri 2018

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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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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

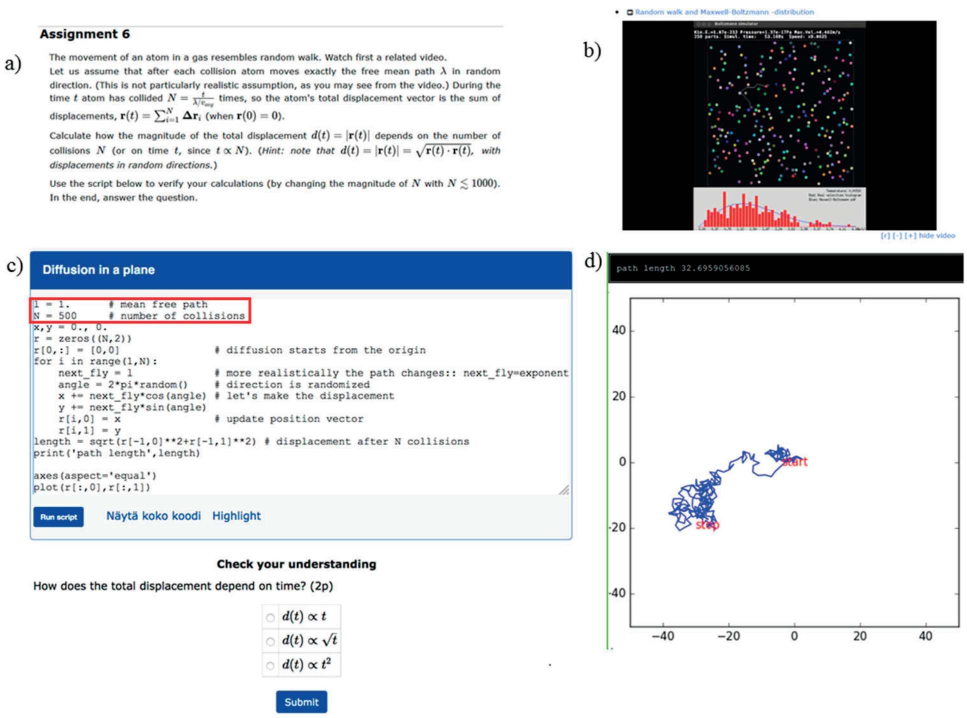


Figure 1. (a) Screen capture of the studied assignment; (b) Screen capture of the video clip; (c) Screen capture of the script. The parameters changed by the students are highlighted in red. (d) Example of the output (path length, i.e. the displacement of an atom and the graphical representation of its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

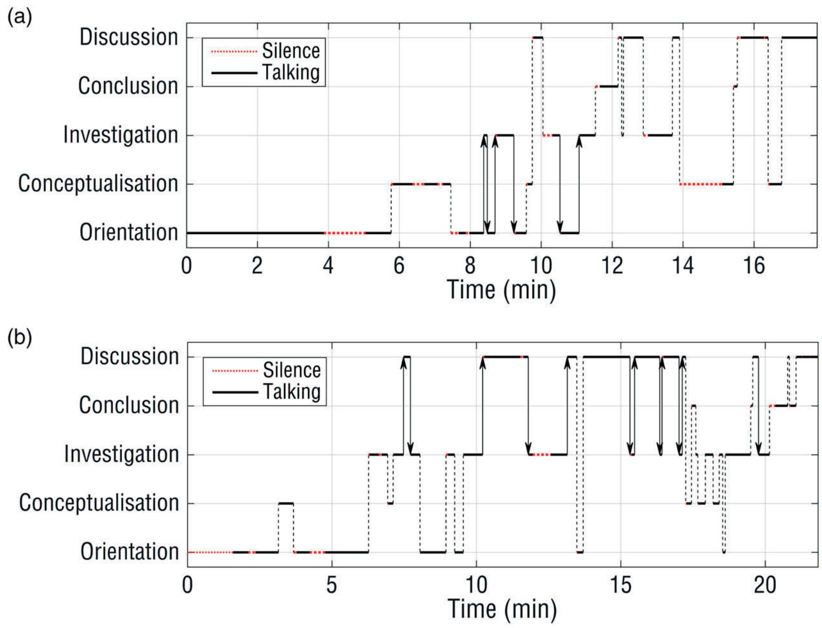


Figure 2. The overall picture of the IBL process of (a) Group 1 and (b) Group 2. The most frequent transitions between the IBL phases are marked with arrows.

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

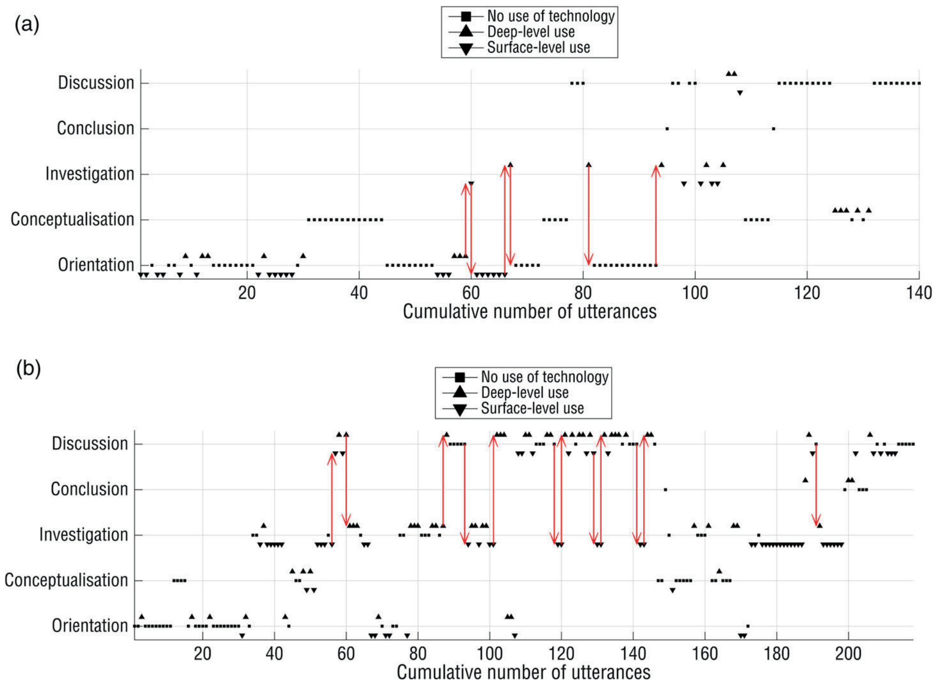


Figure 3. Utilisation of the technological tools in the different IBL phases of (a) Group 1 and (b) Group 2. Symbols represent utterances. The most frequent transitions between the IBL phases are marked with arrows.

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

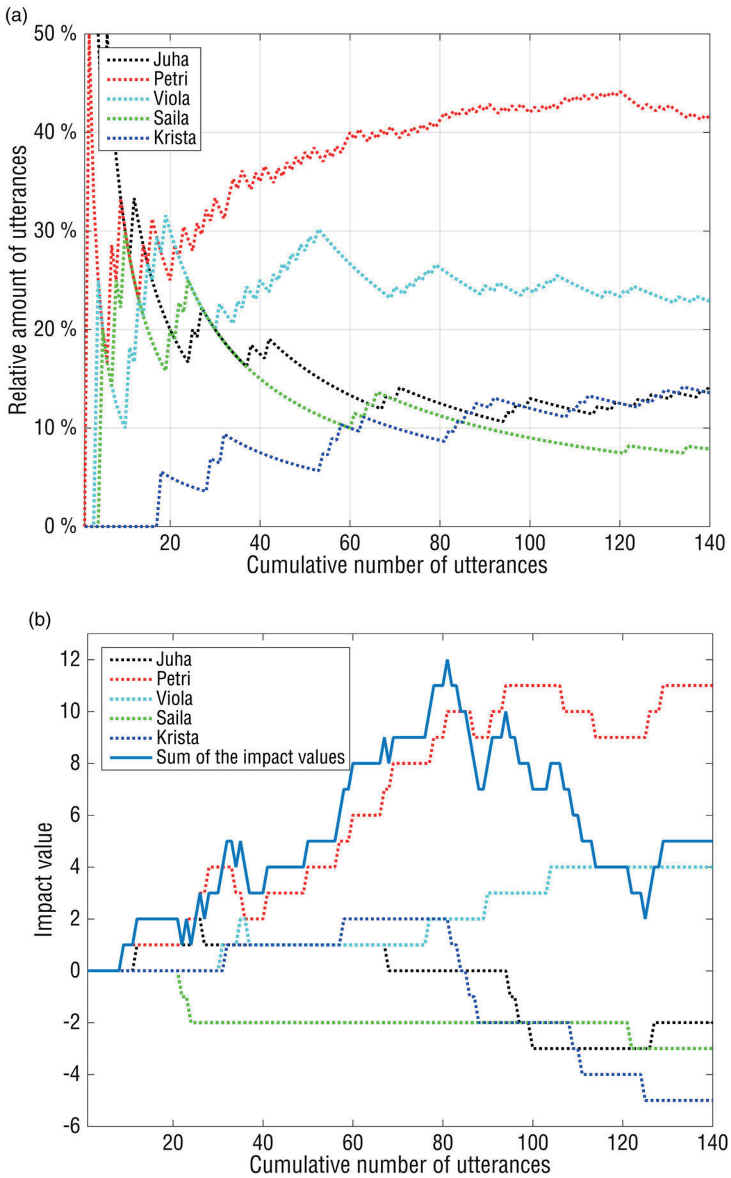


Figure 4. Group 1. (a) Development of participation (in)equity in the collaborative learning process. (b) Development of different students' impact values on the collaborative learning process.

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.

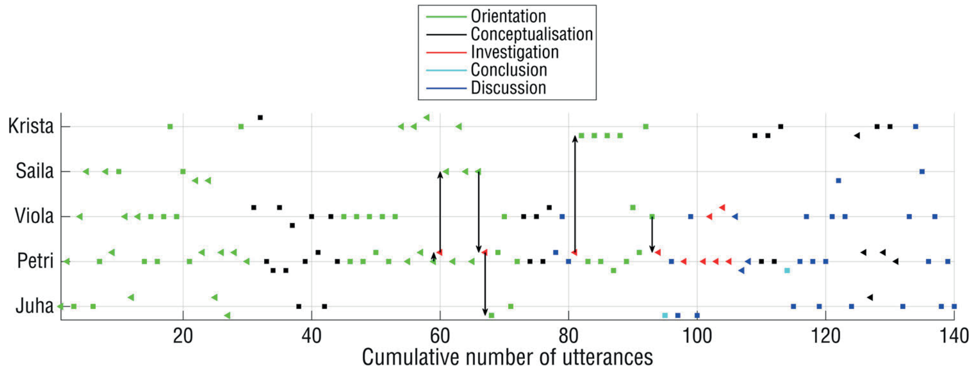


Figure 5. Group 1: The overall picture of the technology-enhanced CIBL process. The IBL phases are marked with different colours. Symbols represent utterances. Triangles indicate utterances that included a reference to the technological tools. The symbol is above/below/on a horizontal axis if the utterance 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.

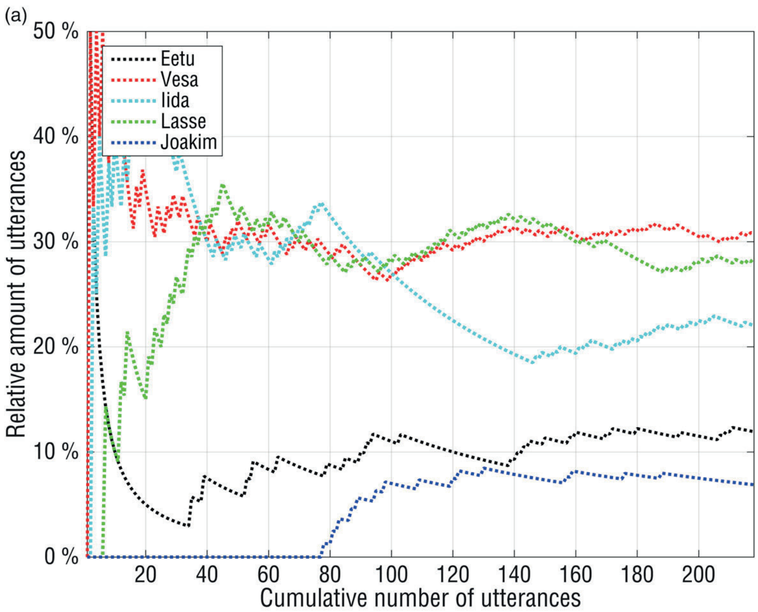
Table 9. Group 2: Cumulative number of utterances in the different IBL phases; the cumulative number of utterances referring to the technological learning resources are presented in parentheses.

	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



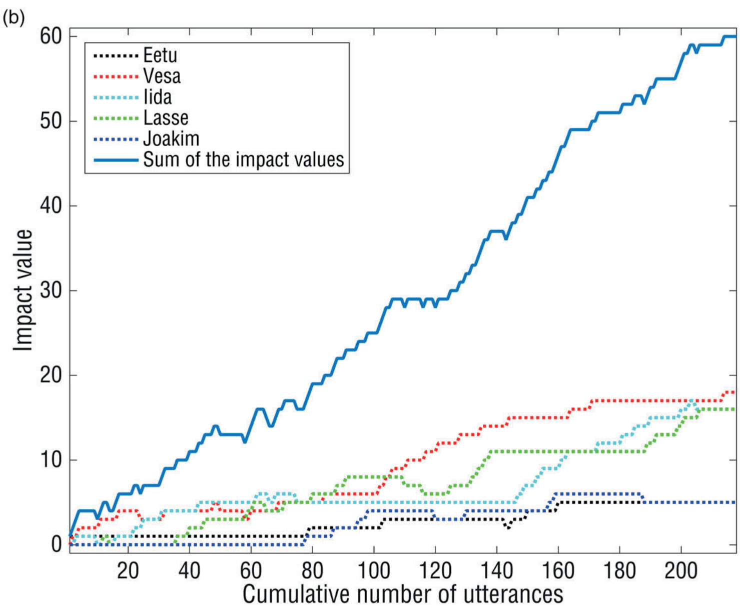


Figure 6. Group 2. (a) Development of participation (in)equity in the collaborative learning process. (b) Development of different students' impact values on the collaborative learning process.

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

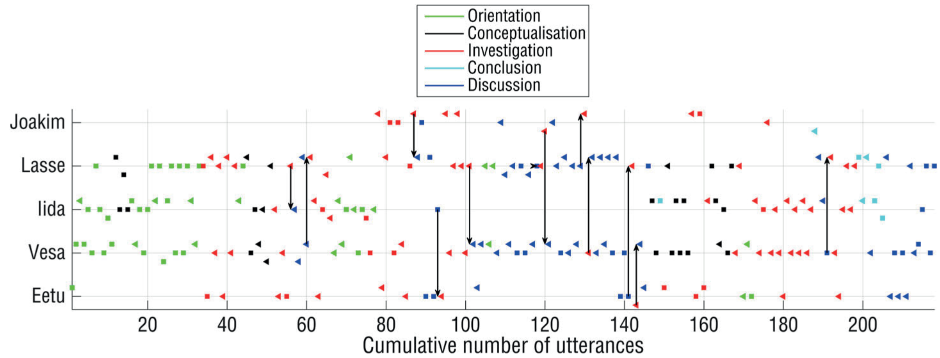


Figure 7. Group 2: The overall picture of the technology-enhanced CIBL process. The IBL phases are marked with different colours. Symbols represent utterances. Triangles indicate utterances that included a reference to the technological tools. The symbol is above/below/on a horizontal axis if the utterance 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.

IV

THE POTENTIAL OF TEMPORAL ANALYSIS: COMBINING LOG DATA AND LAG SEQUENTIAL ANALYSIS TO INVESTIGATE TEMPORAL DIFFERENCES BETWEEN SCAFFOLDED AND NON-SCAFFOLDED GROUP INQUIRY-BASED LEARNING PROCESSES

by

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The potential of temporal analysis: Combining log data and lag sequential analysis to investigate temporal differences between scaffolded and non-scaffolded group inquiry-based learning processes

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A B S T R A C T

This paper contributes to the ongoing discussion about analysing the temporal aspects of learning processes in the educational technology research field. Our main aim was to advance methods for analysing temporal aspects of technology-enhanced learning (TEL) processes by introducing the temporal lag sequential analysis (TLSA) technique and by combining TLSA with temporal log data analysis (TLDA). Our secondary aim was to illustrate the potential of these two analysis techniques to reveal the differences between the face-to-face technology-enhanced collaborative inquiry-based learning (CIBL) processes of three different conditions (non-scaffolded, writing scaffolded and script scaffolded groups). The study involved undergraduate university students ($N = 231$) in natural sciences. The TLDA was based on timestamps and groups' inputs into a TEL environment, and it focused on the groups' temporal ways of using technological resources. The TLSA was based on screen capture videos and audio recordings of the groups' CIBL processes, and it focused on the inquiry-based learning (IBL) transition patterns (i.e. the transitions between the different IBL phases) discovered by lag sequential analysis and demonstrated by how the IBL transition patterns temporarily emerged. The TLDA findings demonstrated temporal differences regarding how the groups in the different conditions used the available technological resources. The TLSA findings revealed three temporarily distinct IBL transition pattern clusters whose content and temporal emergence varied depending on the condition. Parallel temporal analysis of the log data and the IBL transition patterns indicated that the use of the technological resources temporarily mediated IBL transition patterns. Specifically, we found advantages similar to those of asynchronous online discussions (think before acting) when face-to-face interaction was enhanced with the writing scaffold. The article concludes with a general discussion of the necessity and potential of temporal analysis.

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1. Introduction

Learning is a continuous and dynamic process that evolves as a function of time (Kapur, 2011; Mercer, 2008). This fundamental relationship between time and learning has led many researchers to examine the temporal aspects of learning processes in the educational technology research field (Chang, Chang, Liu, Chiu, Fan Chiang, Wen et al., 2017; Chiang, Yang, & Hwang, 2014; Csanadi, Eagan, Kollar, Shaffer, & Fischer, 2018; Kapur, 2011; Knight, Wise, & Chen, 2017; Lin, Duh, Li, Wang, & Tsai, 2013; Popov, van Leeuwen, & Buis, 2017; Reimann, 2009; Wise & Chiu, 2011). The change in methodological orientation can be associated with the ease of collecting and analysing learning process data due to technological developments. For example, when students work in technological learning environments, their log data with events, and even their timestamps can be automatically captured. Moreover, it has been noted that a pure 'coding-and-counting' approach is not enough when analysing complex technology-enhanced learning (TEL) processes (Csanadi et al., 2018; Kapur, 2011). The problem with reporting mere descriptive statistics regarding learning activities is that it makes an implicit assumption about temporal homogeneity of learning (Kapur, Voiklis, & Kinzer, 2008) that may lead to inadequate or even incorrect conclusions about learning processes (Csanadi et al., 2018).

In the context of technology-enhanced collaborative inquiry-based learning (CIBL), for example, the dynamic interplay of different aspects of learning (e.g. related to content or related to technological resources; see Oner, 2013) can become visible as a non-linear process between the different phases of inquiry-based learning (IBL) (e.g.(Lämsä, Hämäläinen, Koskinen, & Viiri, 2018)), which cannot be captured with the help of descriptive statistics. While different types of scaffolds have been provided for students to handle this dynamic interplay and to achieve the many advantages of technology-enhanced CIBL (Bell, Urhahne, Schanze, & Ploetzner, 2010; Jensen & Lawson, 2011; Sins, Savelsbergh, van Joolingen, & van Hout-Wolters, 2011), few studies have examined the temporal aspects of the learning processes behind the observed changes in learning outcomes or the descriptive statistics of learning activities (Balgopal, Casper, Atadero, & Rambo-Hernandez, 2017; Chen, Wang, Grotzer, & Dede, 2018; Gijlers & de Jong, 2013; Hsu, Chiu, Lin, & Wang, 2015; Rau, Bowman, & Moore, 2017; Saab, van Joolingen, & van Hout-Wolters, 2012; Yücel & Usluel, 2016). Focusing on temporal aspects of scaffolded technology-enhanced CIBL processes, however, can reveal how students use the scaffolds, which indicates whether the actual usage differs from the designed usage of the scaffolds. This kind of information can provide valuable insights into how to redesign and implement scaffolds to enhance students' learning processes further.

In this paper, we first advance methods to analyse the temporal aspects of TEL processes. Second, we illustrate the potential of these novel methods when comparing non-scaffolded and scaffolded technology-enhanced CIBL processes taking place in face-to-face interactions (the focus has previously been on temporal aspects of online discussions) (Chang, Chang, Liu et al., 2017; Kucuk & Sisman, 2017; Liao, Chen, & Shih, 2019; Tawfik et al., 2018; Wang, Duh, Li, Lin, & Tsai, 2014; Yang, Li, & Xing, 2018; Zhang, Liu, Chen, Wang, & Huang, 2017). In the following, we present the theoretical framework for our study. We start by elaborating the need for new methods that can be used to analyse temporal aspects of TEL processes. We follow that by introducing the context in which the potential of new methods is illustrated, i.e. technology-enhanced CIBL enhanced by two different scaffolds.

2. Theoretical framework

2.1. *Temporal analysis*

Recently, there has been a growing interest in analysing the temporal aspects of learning processes in various contexts in the educational technology research field (; Chang, Chang, Liu et al., 2017; Chiang et al., 2014; Lämsä et al., 2018/ce:cross-ref > ; Lin et al., 2013; Popov et al., 2017; Sobocinski, Malmberg, & Järvelä, 2017; Wang et al., 2014; Wise & Chiu, 2011). As there are different definitions of 'temporality' (Knight et al., 2017), it is important to pinpoint the kind of temporality the analysis method focuses on. The temporality can refer to behaviour patterns in learning processes without indicating the instant of time or mutual order of the patterns (Knight et al., 2017). As an example of this kind of method, lag sequential analysis (LSA) Bakeman & Gottman, 1997) has recently been conducted in online learning contexts to reveal two or more episodes (called *lags*) that occur in a sequence more often than would be expected by chance (Chang, Chang, Liu et al., 2017; Kucuk & Sisman, 2017; Liao et al., 2019; Tawfik et al., 2018; Wang et al., 2014; Yang et al., 2018; Zhang et al., 2017). Although current discussion has provided insights on productive or unproductive patterns of learning processes, little attention has been paid to the mutual order or the averaged time instants of the identified patterns. These aspects, however, can play a crucial role in learning processes: for example, Kapur et al. (2008) found that the first third of technology-enhanced collaborative learning processes may predict the eventual learning performance. Thus, we need to advance the LSA method so that it takes into account another understanding of temporality, namely, that temporality can also refer to the explicit monitoring of time from the viewpoint of timestamps or the duration of the specific learning activity (Knight et al., 2017).

Temporal lag sequential analysis (TLSA), introduced and implemented in this study, advances LSA to determine the averaged time instant for each identified pattern, which provides several advantages. First, TLSA reveals the mutual order of the identified patterns, which can increase our understanding about the progression of learning processes. Without information about the mutual order of the patterns, it can be tempting to draw non-justified conclusions about the actual progress of learning processes; for example, if specific patterns are expected to be consecutive, LSA alone is not enough to guarantee what is the actual order of the patterns. Second, TLSA can reveal what kind of patterns are 'clustered' together (i.e. emerge close to each other in the timeline). These clusters can guide researchers and teachers to find broader phases of learning processes as individual patterns may sometimes be problematic to interpret (Csanadi et al., 2018). Studying the mutual order of the patterns and the formed clusters may also provide added value when comparing the learning processes between different groups. For example, when visualising the identified patterns as a function of time, we can identify whether differences between the groups arise at the beginning of learning processes or during the learning processes. While TLSA provides insights on the behaviour patterns of the learning processes, the mutual order of the patterns and the evolvement of the learning processes, it does not elucidate any explanations behind these findings. Thus, methodological triangulation can provide added value to the analyses. In technology-enhanced contexts, learning process data can be automatically captured in the form of log data with events and timestamps. The log data continuously capture students' use of the technological resources, which plays an important role in their learning patterns (Chang, Chang, Chiu, Liu, Fan Chiang, Wen et al., 2017; Chang, Chang, Liu et al., 2017; Chiang et al., 2014; Lämsä et al., 2018; Lin et al., 2013; Wang et al., 2014; Wu, 2019). Thus, TLSA and temporal log data analysis (TLDA) could potentially supplement each other.

One advantage of TLDA is that it enables the study of a large number of students over different time frames compared to more traditional and time-consuming analysis of videos and audio recordings. Many authors (Chang, Chang, Chiu et al., 2017; Chang, Chang, Liu et al., 2017; Wu, 2019) have already illustrated the potential of combining TLDA and LSA by examining the use of technological resources in the context of collaborative problem solving. This methodological triangulation may have also dispelled the doubts related to the use of log data; for example, Wise and Schwarz (2017) saw the log data and related methodological approaches as one of the deniable issues in the community of technology-enhanced collaborative learning. We argue that the full potential of this kind of methodological triangulation can be achieved by combining TLDA and TLSA. This combination enables us to pay attention both to the use of technological resources and to the identified behaviour patterns as a function of time (cf. Oner, 2013). Even though this kind of analysis does not allow the identification of causal relationships between the use of resources and the behaviour patterns, it can function as a theoretical lens to illuminate more explicitly how these two aspects are interrelated. In the present study, we illustrate the potential of combining TLDA and TLSA in the context of technology-enhanced CIBL.

2.2. Technology-enhanced collaborative inquiry-based learning

We refer to CIBL as a process in which students in a group follow the practices of scientists to learn scientific content and to apply skills to acquire scientific knowledge together with others and understand the nature of science better (Bell et al., 2010; Jensen & Lawson, 2011; Sins et al., 2011). The essential aspects of CIBL can be captured with the help of five inquiry phases—orientation, conceptualisation, investigation, conclusion and discussion—as presented by Pedaste, Mäeots, Siiman, de Jong, van Riesen, Siswa et al. (2015). In the orientation phase, students stimulate interest and curiosity in relation to the problem. They also identify the main concepts of the assignment and become familiar with technological resources. In the conceptualisation phase, students determine the dependent and independent variables that are needed to solve the problem. In this phase, generating research questions and hypotheses are essential. In the investigation phase, students plan data collection and explore, collect, analyse and interpret data. In the conclusion phase, students offer and evaluate solutions to the research questions and hypotheses. In the discussion phase, students communicate and elaborate their findings and conclusions. This phase is also characterised by reflection of either the entire IBL process after its completion or a single phase during the process.

In natural sciences, such as physics, CIBL has traditionally been conducted as a part of hands-on laboratory work in order for technological resources to support data collection, analysis and reporting (Andersson & Enghag, 2017). Moreover, collaboration between students might have been technology mediated. It has recently become more typical that phenomena themselves are discovered with the help of technological resources such as simulations (Chang, Chang, Liu et al., 2017) or programs for numerical problem solving (Kortemeyer & Kortemeyer, 2018). This change has been associated with the technological development that has simultaneously made these resources available for most students. Despite various possibilities and benefits to implement technology-enhanced CIBL activities, Alfieri, Brooks, Aldrich, and Tenenbaum (2011) noted that the full potential of IBL can be achieved only when the learning is assisted. In addition, many studies (e.g. Ibáñez & Delgado-Kloos, 2018; Lämsä et al., 2018; Rau et al., 2017) have corroborated that scaffolds are needed to enhance technology-enhanced CIBL processes.

2.3. Scaffolding

Due to the complex nature of technology-enhanced CIBL, the many ways to scaffold these learning processes have been implemented and studied. In general, scaffolding refers to a process in which an agent (e.g. teacher, peer and/or computer software) helps a student with tasks that are challenging to complete (Wood, Bruner, & Ross, 1976). In this study, *scaffold* refers to procedural support in a TEL environment that guides students to engage in CIBL (see Kim & Hannafin, 2011; Quintana, Reiser, Davis, Krajcik, Fretz, Duncan et al., 2004; Sharma & Hannafin, 2007). As an example of this kind of scaffold, integrating writing tools into learning environments—where students write down planned steps for IBL processes—could help students by externalising their understanding (Gijlers, Saab, van Joolingen, de Jong, & van Hout-Wolters, 2009; Hmelo-Silver, Duncan, & Chinn, 2007; Sharma & Hannafin, 2007). For example, van Joolingen and de Jong (1991) discovered that when students have problems in conceptualising the inquiry problem at hand, hypothesis scratchpads have proven to be useful in writing hypotheses. The externalisation of their own thinking may make it easier for everyone in a group to follow the joint CIBL process and express differing opinions (Chen et al., 2018; Gijlers & de Jong, 2013).

As another example of these procedural scaffolds, many studies have illustrated the positive effects of socio-cognitive scaffolding via collaboration scripts (De Wever, Hämäläinen, Voet, & Gielen, 2015; Fischer, Kollar, Stegmann, & Wecker, 2013; Rau et al., 2017; Vogel, Wecker, Kollar, & Fischer, 2017; Wang, Kollar, & Stegmann, 2017). To enhance productive collaboration activities, such as students asking each other questions and each student explaining his or her own understanding, the potential of collaboration scripts has also been recognised in CIBL contexts (Kollar, Fischer, & Slotta, 2007; Mäkitalo-Siegl, Kohnle, & Fischer, 2011; Raes, Schellens, De Wever, & Vanderhoven, 2012). Collaboration scripts aim to ‘facilitate both social and cognitive processes of learning by shaping the way learners interact with each other' (Kobbe et al., 2007, p. 211). In the technology-enhanced CIBL context, *activities* (Kobbe et al., 2007) described in the script can be based on the IBL phases (e.g. orientation, conceptualisation, investigation, conclusion and discussion, Pedaste et al., 2015) so that each student is given *a role* based on one of the IBL phases (five *participants*) with hints to use the available technological *resources*.

The effect of different scaffolds (e.g. writing tools for the specific phases of IBL or enhancing CIBL with collaboration scripts) on technology-enhanced CIBL processes have been examined from the viewpoint of learning outcomes and cumulative frequency counts of learning processes (Balgopal et al., 2017; Chen et al., 2018; Gijlers & de Jong, 2013; Hsu et al., 2015; Rau et al., 2017; Saab et al., 2012; Yücel & Usluel, 2016). A recent meta-analysis indicated clear positive effects on cognitive outcomes, especially among adults, regardless of the type of computer-based scaffold used (e.g. whether generic or context specific, explicitly added or faded, etc.) (Belland, Walker, Kim, & Lefler, 2017; Lazonder & Harmsen, 2016). Even though these studies indicate that there is a change in learning outcomes or activities associated with the scaffolds provided, they do not describe how the change took place (Kapur, 2011; Mercer, 2008; Stahl, 2017). This information, however, can be essential from the viewpoint of designing and implementing scaffolds in order to understand better how students perceive and use the scaffolds.

When designing and implementing procedural scaffolds for technology-enhanced CIBL, a certain type of progress in IBL transition patterns (discovered with TLSA) is fostered (cf. Pedaste et al., 2015). Because our previous findings indicated that the groups' ways of using technological resources may trigger these IBL transition patterns (Lämsä et al., 2018), we continue studying the interplay between the use of the technological resources and the progress of IBL transition patterns. Namely, in the present study, TLDA and TLSA function as a lens for understanding possible differences between scaffolded and non-scaffolded technology-enhanced CIBL processes taking place in face-to-face interactions.

3. Aims

The main aim of our study was to advance methods for analysing temporal aspects of TEL processes by introducing the TLSA technique. Moreover, we supplemented TLSA with TLDA. *A secondary aim was to illustrate the potential of these two temporal analysis techniques in the context of technology-enhanced CIBL, which was enhanced by two different scaffolds*. We investigated how the scaffolds (facilitation of IBL through writing and facilitation of CIBL with collaboration scripts) were associated with the use of technological resources and the IBL transition patterns of the scaffolded groups (conditions 1 and 2, respectively) compared to the non-scaffolded groups (condition 3) when the groups were working face-to-face. For this illustration, we addressed the following research questions (RQs):

1. How are the technological resources used in three different conditions, and what are the temporal distinctions between these conditions?
2. What kinds of IBL transition patterns do the three different conditions exhibit, and how do the IBL transition patterns differ between these conditions?
3. How do the IBL transition patterns temporally emerge in the three different conditions, and what are the temporal distinctions between these conditions?

4. Material and methods

4.1. Context and participants

Our study was conducted in an introductory thermodynamics course at a Finnish University (for a detailed description of the course structure, see Koskinen, Lämsä, Maunuksela, Hämäläinen, & Viiri, 2018). The 231 participants were undergraduate natural science students. The participants were divided into groups of five students at the beginning of the course. In total, there were 46 groups (seven groups included four or six students). The groups were heterogeneous regarding gender, major and performance in the course (measured by the results of pre- and post-tests which are not in the focus of this study). During the course, the groups solved problems collaboratively face-to-face in a TEL environment with a shared laptop computer twice a week. Each session typically contained five to seven problems. No teachers or researchers were present in these group working sessions. In the following section, we will present the procedure of this study in detail. The overview of the procedure is presented in Fig. 1.

4.2. Procedure

Log data were collected from the TEL environment of all groups and included timestamps and the groups' inputs into the environment. We focused on the problems that included technological resources (simulations, videos, Python programs) which engaged the students in technology-enhanced CIBL. Based on the data of 14 groups ($n_{\text{student}} = 70$; see Fig. 1), we identified the most challenging problems by determining the number of correct and incorrect answers based on the log data. For more detailed analysis, we selected the problem to which the groups had devoted the most time: studying how the displacement of an atom in a two-dimensional gas depends on time (Fig. 2a). The groups had access to a Python program (Fig. 2b) that plotted atom's path and calculated its total displacement (Fig. 2c). The students were able to change the values of the variables in the Python program to observe how the changes affected the displacement. The solution of the problem required that the groups (a) run the Python program with different values of N (i.e. the number of collisions, which is directly proportional to amount of time) and (b) run the Python program multiple times with the same value of N to infer the time dependence of the averaged value of the displacement (cf. 'Tasks' in the investigation

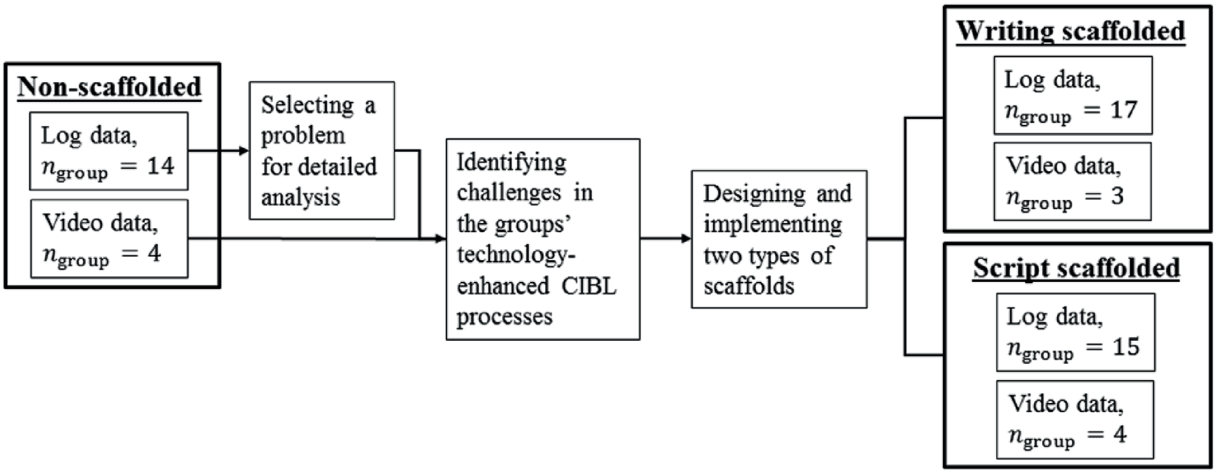

Fig. 1. The procedure of the study.

phase in Table 1).

In addition to the log data, 11 randomly selected follow-up groups screen captured and audio recorded their group working sessions by using Screencast-O-Matic software. The screen capture videos revealed the groups' computer use in the TEL environment. We identified challenges in four non-scaffolded follow-up groups' technology-enhanced CIBL processes based on the screen capture videos, as shown in Fig. 1 (Lämsä et al., 2018). The challenges were related to the first phases of IBL (especially to orientation and conceptualisation) and to systematic ways of using the technological resources during the investigation phase (see 'Challenges' in Table 1). As Fig. 1 suggests, these empirically identified challenges formed the basis for the design of the scaffolds; however, previous research has identified similar challenges in different contexts (Chang, Chang, Liu et al., 2017; Kapur et al., 2008; Koretsky, Brooks, & Higgins, 2016; Wang et al., 2014). The general aim of the scaffolds implemented in the TEL environment was to provide procedural guidance for the CIBL process and hints to use the provided technological resources as part of the students' learning process.

In total, 17 groups ($n_{student}$ = 86; video and audio data from three follow-up groups, see Fig. 1) were instructed to write down essential aspects of the orientation, conceptualisation and investigation phases in the TEL environment (writing scaffold; see Table 1). We integrated the text boxes into the TEL environment so that, for each phase, the groups had a separate place where one of the students could write down the group's joint answer. Even though the writing scaffold focused on the first three phases of IBL, we also expected it both to enable the groups to make justified conclusions about the problem and to foster discussion in the groups. Respectively, 15 groups ($n_{student}$ = 75; video and audio data from four follow-up groups, see Fig. 1) were instructed to adopt student roles (cf. scripting in collaborative learning; Kobbe et al., 2007). As roles are key components of scripting (Dillenbourg & Hong, 2008; Kobbe et al., 2007) and the groups included five students, we created five roles based on the IBL phases (script scaffold; see Table 1). This design choice led us to give non-specific guidelines for the script-scaffolded groups to follow in both the conclusion and the discussion phases. The content of two scaffolds was similar in the orientation, conceptualisation and investigation phases (Table 1).

4.3. Analysis

To answer RQ1—How are the technological resources used in three different conditions, and what are the temporal distinctions between these conditions?—we analysed the groups' use of the Python program (see Fig. 2b). First, we determined how many different number of collisions (N) values each group used when they ran the Python program. Second, we calculated the average number of times each group ran the Python program with the same value of N. We then compared the results between the different conditions by conducting a Kruskal-Wallis test. A nonparametric test was chosen because the data did not fulfil the assumption of normality. TLDA was based on the timestamps labelled for each run with the Python program. To analyse temporal differences between the conditions, we plotted empirical cumulative distribution functions that visualised the use of the Python program as a function of time in all three different conditions. The empirical cumulative distribution functions show how the relative number of runs with the Python program behaves as a function of time; that is the value of the empirical cumulative distribution (from 0 to 1) indicates the fraction of the total number of runs that have been performed before that time instant. We compared the different conditions by conducting a one-sample Kolmogorov-Smirnov test, which is a nonparametric goodness-of-fit test, to measure how these empirical cumulative distribution functions fit the uniform distribution model with 0 and 1 as the minimum and maximum values. The choice of this uniform distribution is justifiable because the groups could use the Python program or technological resources in general, throughout the inquiry process (Bell et al., 2010). We also conducted a two-sample Kolmogorov-Smirnov test to see if the empirical cumulative distribution functions were similar. Unrounded timestamp values were used to avoid the presence of ties.

To answer RQ2—What kinds of IBL transition patterns do the three different conditions exhibit, and how do the IBL transition patterns differ between these conditions?—we focused on the screen capture videos and audio recordings of 11 follow-up groups.

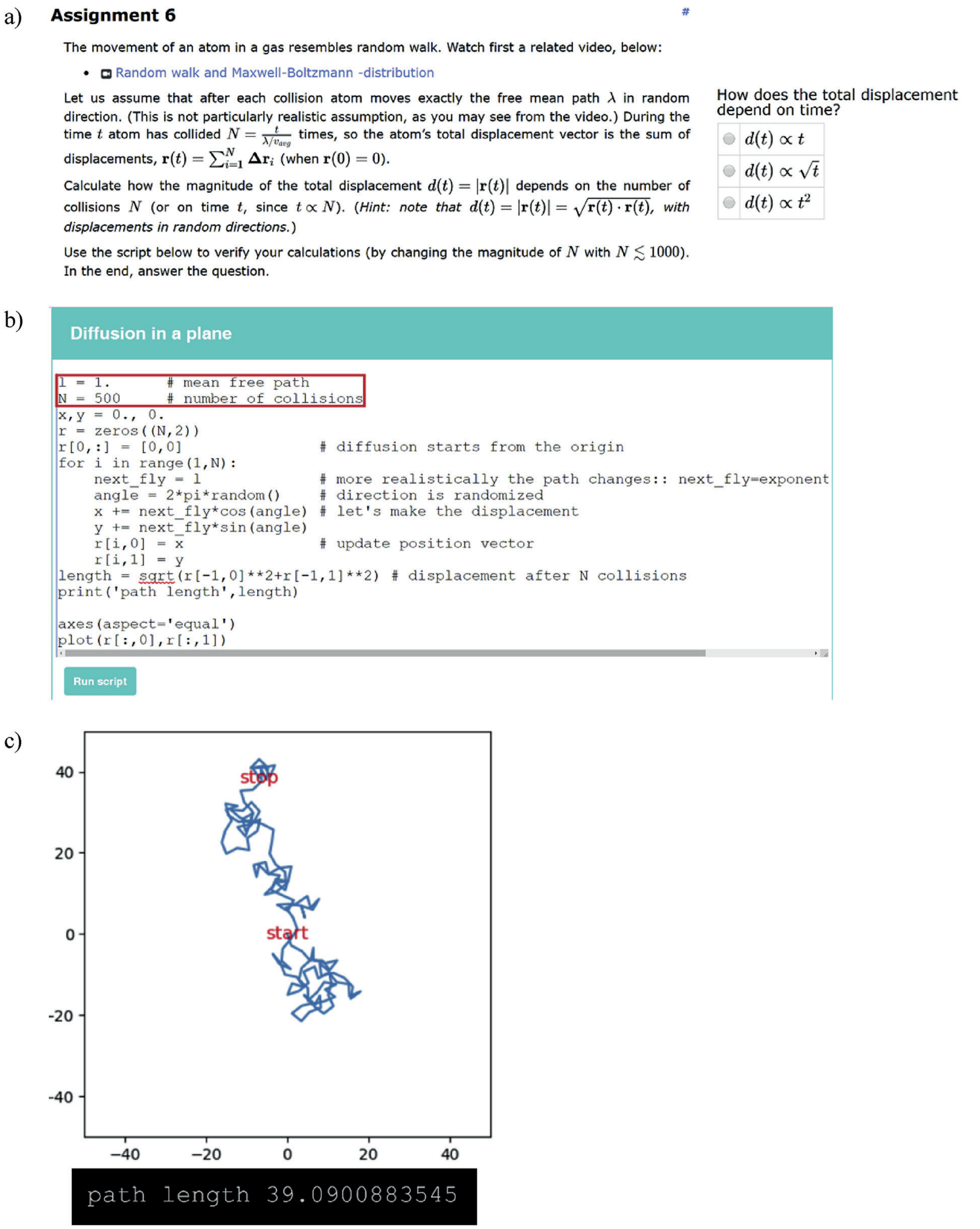

Fig. 2. Screen captures of (a) the random walk problem assignment, (b) Python program (students changed the values of the variables highlighted in red) and (c) output of the Python program that plotted atom's path and calculated its total displacement (path length). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 1
Tasks related to the random walk problem in the different phases of IBL, challenges identified in groups' technology-enhanced CIBL processes and two scaffolds designed to address these challenges.

Phase	Tasks	Challenges	Writing scaffold	Script scaffold
Orientation	Identify the main concepts of the assignment (free mean path, path, total displacement) and become familiar with technological resources (video and Python program).	Become familiar with the technological resources provided.	Write down the key physics concepts of the assignment. Consider how these concepts are represented in the video, in the Python program and in the output of the Python program.	For Student 1: Make sure that everyone in the group identifies the key physics concepts of the assignment. Consider how these concepts are represented in the video, in the Python program and in the output of the Python program.
Conceptualisation	Determine the dependent variables (total displacement) and independent variables (number of collisions and amount of time).	Identify dependent and independent variables from the assignment and from the Python program.	Write down how the question (How does the displacement of an atom in a gas depend on time?) relates to the video, the Python program and the output of the Python program. Reason how you should utilise the Python program so that you are able to answer the question.	For Student 2: Make sure that everyone in the group understands how the question relates to the video, the Python program and the output of the Python program. Reason how you should utilise the Python program so that you are able to answer the question.
Investigation	Plan the data collection procedure, implement the procedure and analyse and interpret the collected data.	Plan and implement a proper data collection strategy.	Write down the joint strategy you will implement so that you are able to answer the question.	For Student 3: Make sure that you plan and implement the joint strategy so that you are able to answer the question.
Conclusion	Offer and evaluate solutions to the given question based on the data.	–	–	For Student 4: Make sure that you make justified conclusions to solve the problem.
Discussion	Elaborate the findings and conclusions, reflecting the joint CIBL process.	–	–	For Student 5: Make sure that you reflect upon your activities throughout the process.

First, we transcribed the groups' talk during the random walk problem (Fig. 2). Second, we identified episodes from the transcribed data. We included as many utterances in an episode as required to understand the episode on its own or, as Henri (1992) put it, to capture a 'unit of meaning'. To improve the reliability of this stage of the analysis, we created guidelines which presented five example episodes with the reasoning behind why the episode captured a 'unit of meaning' from the students' talk. Subsequently, two of us independently identified the episodes from the entire data set, then discussed disagreements and finally resolved the disagreements by consulting others as needed. Third, we conducted theory-driven content analysis (Neuendorf, 2002) for all the episodes and coded the episodes according to the different phases of IBL: orientation, conceptualisation, investigation, conclusion and discussion (Pedaste et al., 2015). These phases, with descriptions and example episodes, are presented in the coding manual (Appendix A). One of us coded all the episodes while another independently coded 20% of the episodes. Cohen's kappa indicated substantial inter-rater reliability ($\kappa = 0.68$; 95% confidence interval = 0.57–0.79). Finally, the disagreements were discussed and completely resolved by consulting others as needed.

To analyse the groups' IBL transition patterns, we performed LSA (Bakeman & Gottman, 1997). In LSA, a unit of analysis is the sequence of two consecutive episodes (coded during the previous step). It was possible for two consecutive episodes to be coded to the same phase of IBL. Next, we tabulated the cumulative number of each IBL transition pattern of the groups separately for each condition. By following a widely used convention, the rows of the table refer to the preceding episode ('lag 0'), and the columns refer to the following episode ('lag 1'). As we focused on five different IBL phases, there were 25 possible IBL transition patterns. We guaranteed that a sufficient data were analysed by checking that the total sample in each condition was at least six times the number of cells (Bakeman & Gottman, 1997, p. 125). We calculated adjusted residuals (z-scores) for each IBL transition pattern in each condition. The residuals indicate whether the observed frequency of the IBL transition pattern deviates from its expected value; for statistically significant IBL transition patterns, $z > 1.96$ ($p < 0.05$). As the number of tallies affects the z-scores, the use of another index in conjunction with the z-scores is recommended when analysing differences between conditions (McComas et al., 2009; Pohl, Wallner, & Kriglstein, 2016). Thus, we also calculated Yule's Q values for the IBL transition patterns (Bakeman & Gottman, 1997). Yule's Q indicates the strength of the relationship between dichotomous variables. Therefore, we collapsed 5×5 tables, including all the possible IBL transition patterns, into 2×2 tables, resulting in a total of 25 2×2 tables, one for each IBL transition pattern. For the transition pattern A → B (note that A and B may denote the same IBL phase), the cells of the 2×2 tables refer to the frequencies of the transition patterns: (a) A → B, (b) A → not-B, (c) not-A → B and (d) not-A → not-B. Yule's Q is calculated as

$$\text{Yule's } Q = \left(\frac{f_{\text{A}\to\text{B}}}{f_{\text{A}\to\text{not-B}}} - \frac{f_{\text{not-A}\to\text{B}}}{f_{\text{not-A}\to\text{not-B}}}\right)\cdot\left(\frac{f_{\text{A}\to\text{B}}}{f_{\text{A}\to\text{not-B}}} + \frac{f_{\text{not-A}\to\text{B}}}{f_{\text{not-A}\to\text{not-B}}}\right)^{-1},$$

where $f_{i\to j}$:s refers to the frequencies in the corresponding cells. From the formula, Yule's Q belongs to the interval between -1 and 1. In addition, the margin sums of the IBL transition patterns are not needed when Yule's Q is calculated. This property makes it a viable index to analyse the differences between scaffolded and non-scaffolded conditions. If Yule's $Q > 0$, the ratio $f_{\text{A}\to\text{B}}/f_{\text{A}\to\text{not-B}}$ is higher than $f_{\text{not-A}\to\text{B}}/f_{\text{not-A}\to\text{not-B}}$, which indicates a positive association in the transition pattern A → B. We considered only the IBL transition patterns with a Yule's $Q > 0.3$, which indicates a moderate positive association in the transition pattern A → B (Davis, 1971).

To answer RQ3—How do the IBL transition patterns temporally emerge in the three different conditions, and what are the temporal distinctions between these conditions?—we conducted TLSA by determining the averaged time instants of the IBL transition patterns in each condition. For each follow-up group, we calculated the averaged serial number of the utterance for each IBL transition pattern that had occurred at least once. Group-level averages were normalised by the total number of utterances. For each condition, we calculated weighted averaged points in which the IBL transition patterns took place. The weight was the number of times an IBL transition pattern occurred in a group. Subsequently, we visualised the IBL transition patterns with a Yule's $Q > 0.3$ as a function of time.

5. Results

We start by providing the overall picture of the duration and outcomes of the technology-enhanced CIBL processes in non-scaffolded, writing scaffolded and script scaffolded conditions. The descriptive statistics of the log data did not show significant differences between the three conditions regarding the time the groups used within each condition to solve the problem ($\chi^2 = 4.5$, df = 2, $p = 0.10$). Although we found indications that the scaffolds enhanced group performance of technology-enhanced CIBL processes with respect to the relative number of correct answers to the problem, this difference was not statistically significant ($\beta_{\text{writing scaffolded}} = 0.36$, $p = 0.62$; $\beta_{\text{script scaffolded}} = 0.41$, $p = 0.59$). Detailed results of the descriptive statistics are presented in

Table 2
Results based on the log data in three different conditions. Standard deviations are presented in brackets.

	Non-scaffolded		Writing scaffolded		Script scaffolded	
Solution	Correct	Incorrect	Correct	Incorrect	Correct	Incorrect
Number of groups	7	7	10	7	9	6
Average time (min)	24.2 (7.6)	14.0 (7.8)	31.8 (10.6)	21.9 (15.0)	15.3 (7.2)	24.7 (10.9)

Table 3
Results based on the log data in three different conditions. Standard deviations are presented in brackets.

	Non-scaffolded	Writing scaffolded	Script scaffolded
Average number of runs (Python program)	9.5 (5.8)	12.5 (8.0)	14.0 (12.6)
Average number of runs with the same value of N	1.5 (0.5)	1.7 (0.6)	1.6 (0.5)

Table 2.

5.1. Use of technological resources in three different conditions and temporal distinctions between the conditions

The solution of the problem required that the groups (a) run the Python program with different values of N (i.e. the number of collisions) and (b) run the Python program multiple times with the same value of N. Regardless of the condition, these two criteria were (on average) fulfilled as shown in Table 3. No differences between the conditions were found with respect to the number of times the groups used the Python program ($\chi^2 = 0.92$, df = 2, $p = 0.63$). However, standard deviations illustrated notable variation between the groups within the same condition. With respect to the number of runs with the same value of N, the differences between the conditions were not significant ($\chi^2 = 0.85$, df = 2, $p = 0.65$).

Even though the descriptive statistics of the log data (Tables 2 and 3) did not capture significant differences between the conditions, the temporal analysis of the log data did show that the temporal use of the Python program varied depending on the condition. In Fig. 3, we present empirical cumulative distribution functions, which show how the groups in the different conditions ran the Python program as a function of time. Fig. 3 shows that the groups with writing scaffolding used the Python program evenly throughout their CIBL processes, whereas the groups in the non-scaffolded and script scaffolded conditions tinkered with the Python program less frequently at the beginning of their CIBL processes. This finding is supported by a one-sample Kolmogorov-Smirnov test, which shows that the uniform distribution model with 0 and 1 as the minimum and maximum values fits the data of the writing scaffolded condition ($D = 0.069$, $p = 0.26$) but not the data of the non-scaffolded ($D = 0.20$, $p < 0.001$) and script scaffolded conditions ($D = 0.15$, $p < 0.001$). Fig. 3 also shows that the empirical cumulative distribution functions are similar in non-scaffolded and script scaffolded conditions, which is supported by the two-sample Kolmogorov-Smirnov test ($D = 0.095$, $p = 0.45$). The empirical cumulative distribution function of the writing scaffolded condition differed both from the function of the non-scaffolded condition ($D = 0.25$, $p < 0.001$) and from the function of the script scaffolded condition ($D = 0.21$, $p < 0.001$).

In Appendix B, we present the results separately of the log data for the 11 follow-up groups that recorded their group working sessions. Based on these recordings, we will describe differences in technology-enhanced CIBL processes between the conditions based on the results of LSA, which shows the IBL transition patterns. Subsequently, we will present the results of TLSA for each condition to illustrate how the IBL transition patterns temporally emerge.

5.2. IBL transition patterns in three different conditions and differences in the patterns between the conditions

We found at least moderately positive (Yule's $Q > 0.3$) and statistically significant ($z > 1.96$, $p < 0.05$) associations in the IBL

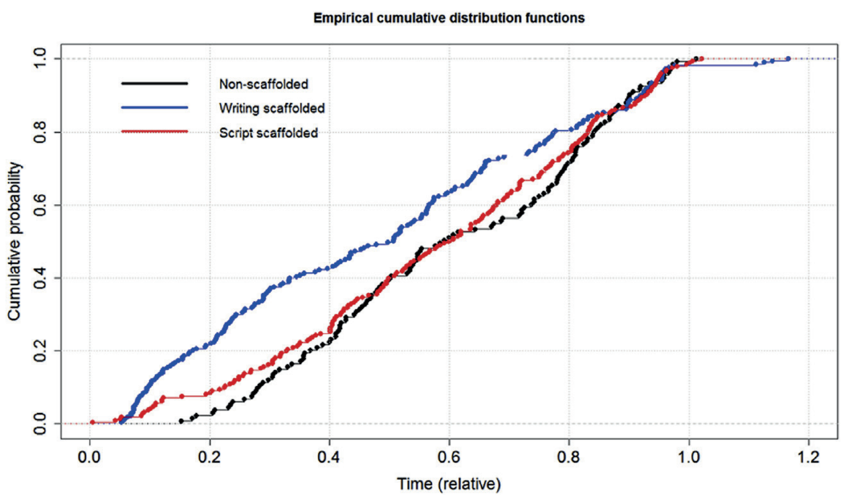

Fig. 3. Empirical cumulative distribution functions of the relative number of runs with the Python program for the groups in three different conditions. In the given instant of time, the value of the function is equal to the fraction of the total number of runs that have been performed before that time instant. Time = 0 refers to the moment when the solution to the previous problem was submitted. Time = 1 refers to the moment when the solution to this random walk problem was submitted.

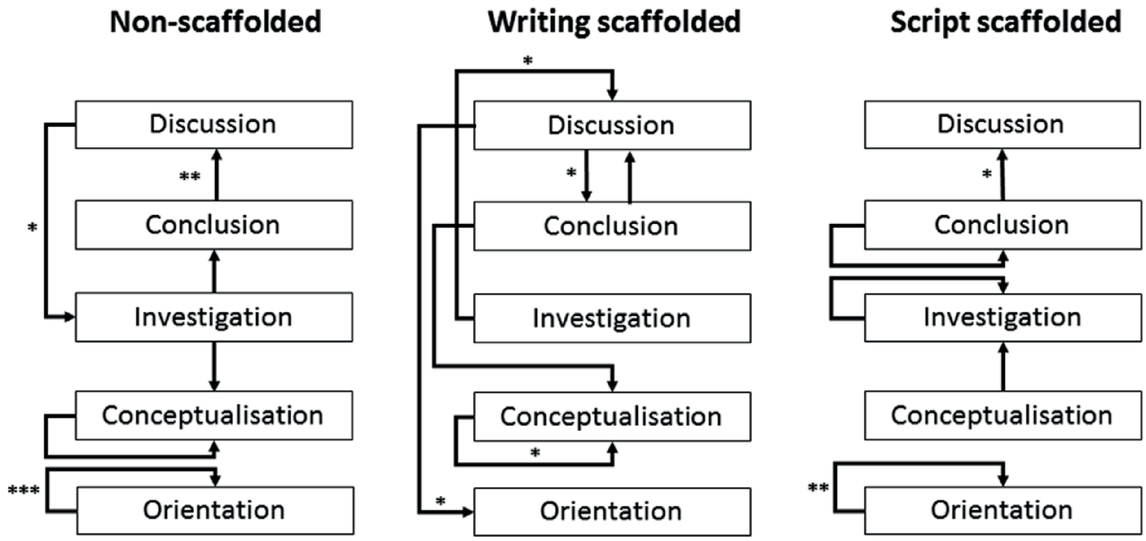

Fig. 4. The IBL transition patterns with Yule's $Q > 0.3$; the statistically significant patterns are marked with asterisks ($*p < 0.05$; $**p < 0.01$; $***p < 0.001$).

transition patterns from all three conditions (see detailed results in Appendix C). These IBL transition patterns are presented in Fig. 4, which shows that there are IBL transition patterns to or from all the different IBL phases in each condition. The non-scaffolded groups have three IBL transition patterns associated with the investigation phase, whereas the groups in the other two conditions have one IBL transition pattern to or from the investigation phase. The groups with writing scaffolding have more IBL transition patterns associated with the discussion phase than the groups in non-scaffolded or script scaffolded conditions. In the script scaffolded condition, three of the five IBL transition patterns iterate in the same phase; this is contrary to the groups in the other two conditions in which most of the IBL transition patterns emerged between the different IBL phases.

5.3. The temporal emergence and distinctions in the IBL transition patterns between three different conditions

We present the IBL transition patterns shown in Fig. 4 as a function of time in Fig. 5 (see detailed results of TLSA in Appendix C). Based on Fig. 5, we identified three temporarily distinct IBL transition pattern clusters from all three conditions. The first transition cluster can be described with the IBL transition patterns associated with the orientation phase. However, this first transition cluster emerged later in the writing scaffolded condition than in the groups of the other two conditions. The groups with writing scaffolding also had recurrent IBL transition patterns in the conceptualisation phase in this first transition cluster. The second transition cluster can be described with the IBL transition patterns associated with the investigation phase. While the conceptualisation phase was included in the first transition cluster in the writing scaffolded condition, the conceptualisation of the groups in non-scaffolded and script scaffolded conditions were related to this second transition cluster. Similar to the first transition cluster, the second transition cluster emerged slightly later in the writing scaffolding groups. The third transition cluster can be described with the IBL transition patterns associated with the conclusion and discussion phases. This transition cluster emerged around the same time in all three conditions. Within the writing scaffolding groups, IBL transition patterns occurred back and forth between the conclusion and the discussion phases in the third transition cluster. In addition, we found the IBL transition pattern from the conclusion to the conceptualisation phase. In the non-scaffolded condition, the IBL transition pattern was found from the investigation to the conclusion phases. Fig. 5 also shows that there is an IBL transition pattern associated with the discussion phase in all three transition clusters in the writing scaffolded condition. However, the preceding or the following phase depends on time, meaning that the discussion phase is associated with the orientation, investigation and conclusion phases, respectively.

6. Discussion

The main aim of this study was to advance methods for analysing temporal aspects of TEL processes by introducing the TLSA technique, which was supplemented with TLDA. In the context of TEL, we see that this kind of methodological triangulation is required to capture interrelated aspects of these learning processes (cf. Oner, 2013). As a secondary aim, we illustrated the potential of these methods to analyse temporal aspects in the context of face-to-face technology-enhanced CIBL processes in three different conditions (non-scaffolded, writing scaffolded and script scaffolded). In this context, parallel analysis of the findings of TLDA and TLSA functions as a lens through which we can see how the use of technological resources (TLDA; RQ1) and IBL transition patterns (TLSA; RQ2–3) are interrelated in different conditions. The actual use of technological resources has been under-represented when studying technology-enhanced CIBL processes (Bernhard, 2018); however, their use during CIBL may be vital for IBL transition patterns (Lämsä et al., 2018). In the following, we elaborate the findings of parallel TLDA and TLSA for non-scaffolded, writing

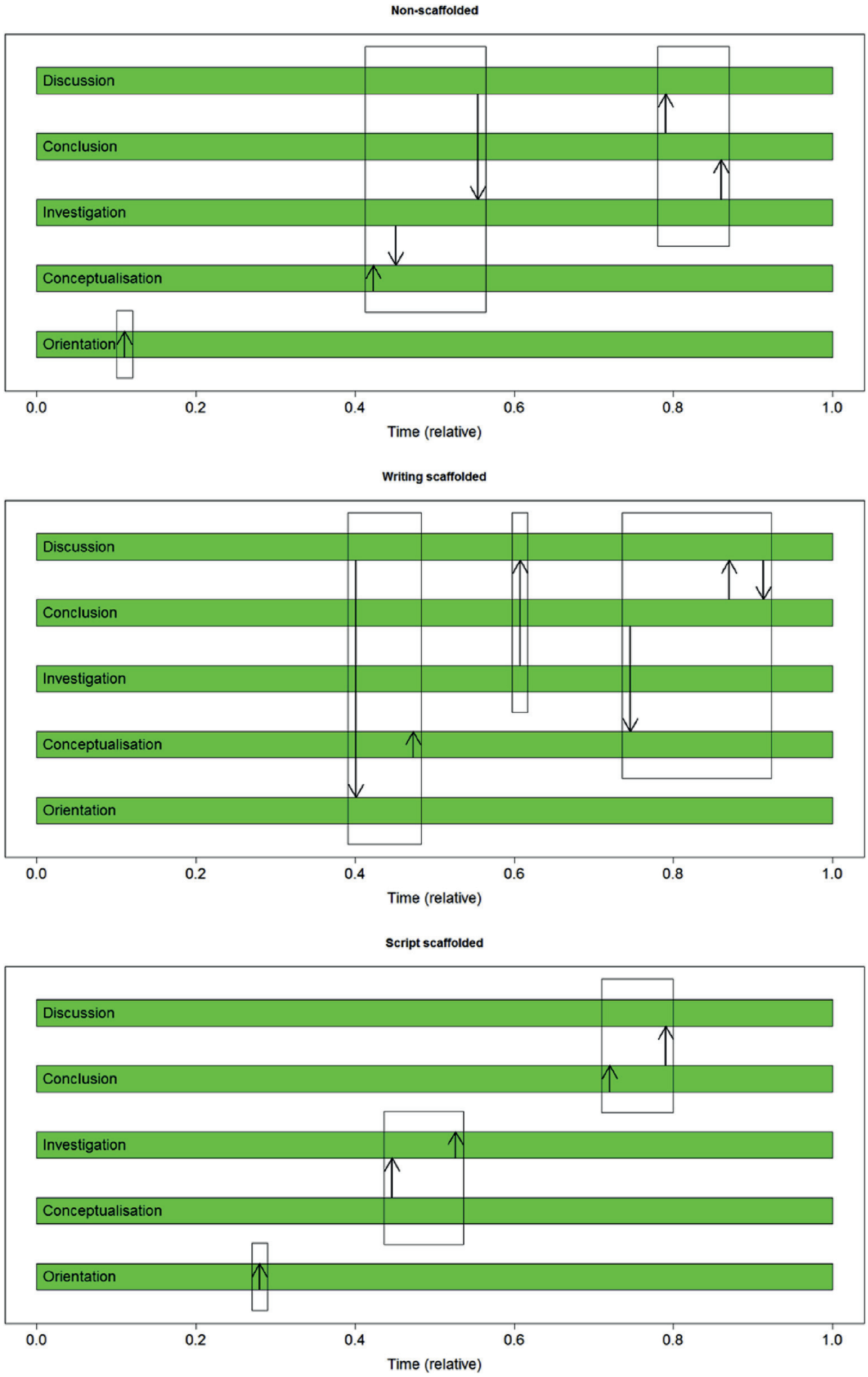

Fig. 5. The IBL transition patterns with Yule's $Q > 0.3$ illustrated as a function of averaged time in the different conditions. Three temporarily distinct transition clusters have been marked with rectangles.

scaffolded and script scaffolded conditions.

Based on the temporal use of technological resources (the Python program) (RQ1) and the temporal emergence of IBL transition patterns (RQ3), the technology-enhanced CIBL processes of the non-scaffolded and script scaffolded groups were similar. In both conditions, the groups used the Python program less frequently at the beginning of their CIBL processes (Fig. 3), and their first transition cluster, which was merely associated with the orientation phase, emerged relatively early (Fig. 5). These results may indicate that the groups in the non-scaffolded and script scaffolded conditions engaged in the actual inquiry at the very beginning and then started to familiarise themselves with the Python program. Before the midpoint of CIBL processes (after relative time instant 0.3 in Fig. 3), these groups started to use the Python program more actively. This change in the slope of the empirical cumulative distribution functions emerged at the same time as the second transition cluster of the non-scaffolded and script scaffolded groups (Fig. 5). The second transition cluster included IBL transition patterns associated with the conceptualisation, investigation and discussion phases. These findings indicate that the conceptualisation of the problem was conducted partly simultaneously with the investigation phase in which the Python program was probably used as a data collection tool.

Conversely, the groups with writing scaffolding used the Python program more frequently at the beginning of their CIBL processes (Fig. 3). Afterwards, these groups did not actively tinker with the Python program (see relative time interval 0.3–0.5 in Fig. 3), but their first transitions cluster emerged (Fig. 5). These results, in turn, indicate that the writing scaffolding guided students to become familiar with the given Python program before they actually engaged in inquiry. This finding was probably related to these groups' instructions, which asked the students to consider and write down how the Python program represented key concepts of the assignment (see the orientation phase in Table 1). Getting to know the properties of the Python program might also contribute to more diverse IBL transition patterns in the first transition cluster compared to the groups in non-scaffolded and script scaffolded conditions: the groups with writing scaffolding had IBL transition patterns associated with the orientation, conceptualisation and discussion phases in the first transition cluster. The findings of the writing scaffolded condition are reminiscent of those from asynchronous online discussions that provide participants the advantage of being able to think and reflect before they actually take action (Clark, Weinberger, Jucks, Spitulnik, & Wallace, 2003; Cohen & Scardamalia, 1998; Veerman, Andriessen, & Kanselaar, 2000; Zion, 2008; Zion, Michalsky, & Mevarech, 2005). After the midpoint of CIBL processes, the slope of the empirical cumulative distribution function of the writing scaffolded condition started to increase again (Fig. 3), which supports the finding of TLSA; these groups also started to investigate and discuss the problem (the second transition cluster in Fig. 5).

Even though the script scaffold included guidance for the conclusion and discussion phases (see Table 1), the last transition cluster emerged at the same time in all three conditions, and the last transition cluster was associated with the conclusion and discussion phases (Fig. 5). Fig. 3 also illustrates that the groups in all conditions took advantage of the Python program until the end of their technology-enhanced CIBL process, including drawing conclusions. The writing scaffold focused on the first three phases of IBL (see Table 1), but it still fostered discussion in the groups as expected. Namely, we found an IBL transition pattern associated with the discussion phase in all three transition clusters in the writing scaffolded condition (Fig. 5).

Despite the similarities in the content of the writing and script scaffolds (Table 1), differences in the groups' technology-enhanced CIBL processes between these two conditions may be mostly explained by the way the students perceived the scaffolds. Namely, the writing scaffold may have been seen more as a part of the problem than as a kind of support. Even though the text boxes in the TEL environment were explicit support from the teachers' perspectives, the videos and audio recordings indicated that students might perceive those as 'faded' (the contrary to explicit scaffolds). This notion is supported by previous studies reporting students using scaffolds in ways that differed from their design (Balgopal et al., 2017; Roll, Butler, Yee, Welsh, Perez, Briseno et al., 2018). On the other hand, the script scaffold with the assigned roles was perceived more like additional guidelines that students dismissed: the videos and audio recordings revealed that although students read the descriptions of the different roles, they did not commit to their own role. This may relate to the established routines for inquiry and collaboration as we focused on the data from the midpoint of the course. The results of the study also support this notion as the technology-enhanced CIBL processes in non-scaffolded and script scaffolded conditions resembled each other based on TLDA (two-sample Kolmogorov-Smirnov tests) and TLSA. Thus, analysing temporal aspects of learning processes may be one way to investigate differences between the 'ideal' script (the learning activities that the script is expected to produce; cf. Kobbe et al., 2007) and the 'actual realised' script (what actually happens in the script scaffolded condition; Dillenbourg & Jermann, 2007).

Methodologically, LSA is one of the emerging methods of studying learning processes in authentic settings. We took LSA one step further by introducing the TLSA technique, which enabled us to capture the differences between the conditions from two viewpoints: (a) the differences between patterns (see Fig. 4) and (b) the temporal emergence of patterns (see Fig. 5). We also used the results of TLDA in addition to TLSA to form a more comprehensive picture of the role of the two scaffolds in groups' technology-enhanced CIBL processes. Even though this research was the first attempt to study whether and how TLDA and TLSA can supplement each other, we were able to find indications that this kind of methodological triangulation may help make more reliable inferences about the temporal aspects of technology-enhanced CIBL processes without exhaustive content analysis methods. Parallel TLDA and TLSA functioned as a lens to reveal otherwise invisible differences between the conditions. Namely, the scaffolds guided groups to use the technological resources (RQ1) differently, which temporarily mediated different IBL transition pattern clusters (RQ2–3). Our method can also be applied to other contexts as the growing need for temporal analysis in educational research has been widely recognised (Barbera, Gros, & Kirschner, 2015; Csanadi et al., 2018; Kapur, 2011; Ludvigsen, Cress, Rosé, Law, & Stahl, 2018; Mercer, 2008; Stahl, 2017). However, we invite researchers to pinpoint the kind of temporality they refer to—namely, whether they refer to explicit monitoring of time from viewpoint of timestamps (RQ1 and RQ3), for instance, or patterns in learning processes without indicating the instant of time or mutual order of the patterns (RQ2). The potential of parallel TLDA and TLSA highlights the need for temporal analysis techniques in which the temporality refers to the explicit monitoring of time.

In addition to the methodological contribution, our study also has other implications. Theoretically, the results of TLSA showed that technology-enhanced CIBL processes taking place in face-to-face contexts in all three conditions were divided into three distinct IBL transition pattern clusters with respect to the temporality and the content (Fig. 5). Even though it is well-known that IBL processes are not linear, and there are IBL transition patterns back and forth between the different IBL phases (Pedaste et al., 2015), TLSA was able to capture the general progress of the technology-enhanced CIBL processes. Namely, IBL transition pattern clusters were associated with the orientation phase first, then with the investigation phase in the middle and, finally, with the conclusion and the discussion phases at the end in all three conditions. The condition, however, seemed to play a role regarding the precise content of the IBL transition pattern clusters as well as the clusters' temporal emergence. Practically, the outcomes of this study may be useful to enhance the future development of technological learning environments regarding adaptive scaffolds. As an example, real-time monitoring of groups' technology-enhanced CIBL processes based on log data (Fig. 3; e.g. Rau et al., 2017) could trigger scaffolds to use available technological resources if the system monitors undesired behaviour (such as no activities for some threshold time interval or exceptional frequent use of resources indicating unsystematic actions, cf. Popov et al., 2017).

The limitations with regard to the findings of the study are, first, that TLDA (RQ1) was based on 46 group inputs and timestamps in the technological learning environment while TLSA (RQ2 and RQ3) was conducted based on 11 follow-up group screen capture videos and audio recordings. Thus, only three or four follow-up groups in each condition restrict the generalisation of our findings. To demonstrate that the follow-up groups in each condition were close to the average, we presented their results separately in Appendix B. The second point, which restricts the generalisation of our findings to other contexts, is that we only focused on a limited amount of data (one problem shown in Fig. 2). The third point restricting the generalisation of our findings is our choice to empirically design the writing scaffold and the script scaffold based on our previously identified challenges (cf. Table 1 and Lämsä et al., 2018). However, there is evidence that the identified challenges may not be context specific (Chang, Chang, Lui et al., 2017; Kapur et al., 2008; Koretsky et al., 2016; Wang et al., 2014). The fourth limitation is that the measurement of time was not completely commensurable between the TLDA and TLSA. When analysing the log data, the time was calculated in relation to the start points and end points of the timestamps. The dimension of time in TLSA was based on the serial number of utterances. There also was a small uncertainty regarding the exact point of the IBL transition pattern because of the method we used to identify episodes based on 'unit of meaning' (Henri, 1992). However, the offset between these two methods of measuring time was not notable.

7. Conclusions

In this research, we first advanced methods for analysing the temporal aspects of TEL processes by introducing the TLSA technique and by supplementing TLSA with TLDA. Subsequently, we illustrated the potential of these two temporal analysis techniques in the context of technology-enhanced CIBL by investigating how two scaffolds (facilitation of IBL through writing and facilitation of CIBL with collaboration scripts) were associated with the technology-enhanced CIBL processes of the scaffolded groups compared to the non-scaffolded groups when the groups were working face-to-face. Regarding RQ1, we found that despite the similarities in descriptive statistics of the log data, there were temporal differences in the manner in which the groups in the different conditions used the technological resources. Regarding RQ2 and RQ3, we found three temporarily distinct IBL transition pattern clusters in each condition. Furthermore, there were temporal differences when each of these IBL transition pattern clusters emerged. By supplementing TLDA (RQ1) with TLSA (RQ3), we found indications that the scaffolds were associated with the use of the technological resources, which in turn temporarily mediated IBL transition patterns. Specifically, the writing scaffold seemed to guide the students to familiarise themselves with and use the available technological resources before they actually engaged in the inquiry and vice versa for the groups in non-scaffolded and script scaffolded conditions. Thus, it seems that the advantages of asynchronous online discussions (e.g. think and reflect before acting) were partly achievable when face-to-face interaction was enhanced by the writing scaffold. In our study, the writing scaffold provided procedural support for the students. Future studies could investigate whether other types of writing scaffolds (e.g. conceptual, metacognitive or strategic; Kim & Hannafin, 2011) have similar advantages and what temporal distinctions exist between different types of writing scaffolds.

Even though the TLDA on its own inhibits making detailed interpretations of learning processes, it remains a potential method to study a large number of students over different time frames. Our study presented novel ways of analysing and visualising log data in conjunction with other learning process data. In this study, we gained a more in-depth picture of group technology-enhanced CIBL processes by using video and audio data. In the future, rapidly developing tools to capture other sorts of learning process data (e.g. eye-tracking data, face recognition data, physiological data or prosodic data) will make it possible for researchers to study temporal aspects of learning processes from various viewpoints. The significance of temporal aspects will probably further increase in the future as automatic analyses of learning processes (e.g. speech recognition and content analysis on the fly) develop and enable educational technologies to provide scaffolds for students in a timely manner.

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Declarations of interest

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Appendix. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.compedu.2019.103674.

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.
Andersson, J., & Enghag, M. (2017). The relation between students' communicative moves during laboratory work in physics and outcomes of their actions. *International Journal of Science Education, 39*(2), 158–180.
Bakeman, R., & Gottman, J. M. (1997). *Observing interaction: An introduction to sequential analysis* (2nd ed.). New York: Cambridge University Press.
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.
Barbera, E., Gros, B., & Kirschner, P. (2015). Paradox of time in research on educational technology. *Time & Society, 24*(1), 96–108.
Belland, B. R., Walker, A. E., Kim, N. J., & Lefler, M. (2017). Synthesizing results from empirical research on computer-based scaffolding in STEM education. *Review of Educational Research, 87*(2), 309–344.
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.
Bernhard, J. (2018). What matters for students' learning in the laboratory? Do not neglect the role of experimental equipment!. *Instructional Science, 46*(6), 819–846.
Chang, C., Chang, M., Chiu, B., Liu, C., Fan Chiang, S., Wen, C., et al. (2017a). An analysis of student collaborative problem solving activities mediated by collaborative simulations. *Computers & Education, 114*, 222–235.
Chang, C., Chang, M., Liu, C., Chiu, B., Fan Chiang, S., Wen, C., et al. (2017b). An analysis of collaborative problem-solving activities mediated by individual-based and collaborative computer simulations. *Journal of Computer Assisted Learning, 33*(6), 649–662.
Chen, J., Wang, M., Grotzer, T. A., & Dede, C. (2018). Using a three-dimensional thinking graph to support inquiry learning. *Journal of Research in Science Teaching, 55*(9), 1239–1263.
Chiang, T. H. C., Yang, S. J. H., & Hwang, G. (2014). Students' online interactive patterns in augmented reality-based inquiry activities. *Computers & Education, 78*, 97–108.
Clark, D. J., Weinberger, A., Jucks, R., Spitulnik, M., & Wallace, R. (2003). Designing effective science inquiry in text-based computer-supported collaborative learning environments. *International Journal of Educational Policy, Research and Practice, 4*(1), 55–82.
Cohen, A., & Scardamalia, M. (1998). Discourse about ideas: Monitoring and regulation in face-to-face and computer-mediated environments. *Interactive Learning Environments, 6*(1–2), 93–113.
Csanadi, A., Eagan, B., Kollar, I., Shaffer, D. W., & Fischer, F. (2018). When coding-and-counting is not enough: Using epistemic network analysis (ENA) to analyze verbal data in CSCL research. *International Journal of Computer-Supported Collaborative Learning, 13*(4), 419–438.
Davis, J. (1971). *Elementary survey analysis* (1st ed.). Englewood Cliffs, NJ: Prentice Hall.
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.
Dillenbourg, P., & Hong, F. (2008). The mechanics of CSCL macro scripts. *International Journal of Computer-Supported Collaborative Learning, 3*(1), 5–23.
Dillenbourg, P., & Jermann, P. (2007). Designing integrative scripts. In F. Fischer, I. Kollar, H. Mandl, & J. M. Haake (Eds.). *Scripting computer-supported collaborative learning*. Boston: Springer.
Fischer, F., Kollar, I., Stegmann, K., & Wecker, C. (2013). Toward a script theory of guidance in computer-supported collaborative learning. *Educational Psychologist, 48*(1), 56–66.
Gijlers, H., & de Jong, T. (2013). Using concept maps to facilitate collaborative simulation-based inquiry learning. *Journal of the Learning Sciences, 22*(3), 340–374.
Gijlers, H., Saab, N., van Joolingen, W. R., de Jong, T., & van Hout-Wolters, B. H. A. M. (2009). Interaction between tool and talk: How instruction and tools support consensus building in collaborative inquiry-learning environments. *Journal of Computer Assisted Learning, 25*(3), 252–267.
Henri, F. (1992). Computer conferencing and content analysis. In A. R. Kaye (Ed.). *Collaborative learning through computer conferencing. The Najadan Papers* (pp. 117–136). London: Springer-Verlag.
Hmelo-Silver, C. E., Duncan, R. G., & Chinn, C. A. (2007). Scaffolding and achievement in problem-based and inquiry learning: A response to Kirschner, Sweller, and Clark (2006). *Educational Psychologist, 42*(2), 99–107.
Hsu, C., Chiu, C., Lin, C., & Wang, T. (2015). Enhancing skill in constructing scientific explanations using a structured argumentation scaffold in scientific inquiry. *Computers & Education, 91*, 46–59.
Ibáñez, M., & Delgado-Kloos, C. (2018). Augmented reality for STEM learning: A systematic review. *Computers & Education, 123*, 109–123.
Jensen, J. L., & Lawson, A. (2011). Effects of collaboration and inquiry on reasoning and achievement in biology. *CBE - Life Science Education, 10*, 64–73.
van Joolingen, W. R., & de Jong, A. J. M. (1991). OCTO-Report*An hypothesis scratchpad as a supportive instrument in simulation learning environmentsVol. 9103*, 1–44.
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.
Kim, M. C., & Hannafin, M. J. (2011). Scaffolding problem solving in technology-enhanced learning environments (TELEs): Bridging research and theory with practice. *Computers & Education, 56*(2), 403–417.
Knight, S., Wise, A. F., & Chen, B. (2017). Time for change: Why learning analytics needs temporal analysis. *Journal of Learning Analytics, 4*(3), 7–17.
Kobbe, L., Weinberger, A., Dillenbourg, P., Harrer, A., Hämäläinen, R., Häkkinen, P., et al. (2007). Specifying computer-supported collaboration scripts. *International Journal of Computer-Supported Collaborative Learning, 2*(2), 211–224.
Kollar, I., Fischer, F., & Slotta, J. D. (2007). Internal and external scripts in computer-supported collaborative inquiry learning. *Learning and Instruction, 17*(6), 708–721.
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.
Kortemeyer, G., & Kortemeyer, A. F. (2018). The nature of collaborations on programming assignments in introductory physics courses: A case study. *European Journal of Physics, 39*(5), 1–20.
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.
Kucuk, S., & Sisman, B. (2017). Behavioral patterns of elementary students and teachers in one-to-one robotics instruction. *Computers & Education, 111*, 31–43.
Lämsä, J., Hämäläinen, R., Koskinen, P., & Viiri, J. (2018). Visualising the temporal aspects of collaborative inquiry-based learning processes in technology-enhanced physics learning. *International Journal of Science Education, 40*(14), 1697–1717.

Lazonder, A., & Harmsen, R. (2016). Meta-analysis of inquiry-based learning: Effects of guidance. *Review of Educational Research, 86*(3), 681–718.
Liao, C., Chen, C., & Shih, S. (2019). The interactivity of video and collaboration for learning achievement, intrinsic motivation, cognitive load, and behavior patterns in a digital game-based learning environment. *Computers & Education, 133*, 43–55.
Lin, T., Duh, H. B., Li, N., Wang, H., & Tsai, C. (2013). An investigation of learners' collaborative knowledge construction performances and behavior patterns in an augmented reality simulation system. *Computers & Education, 68*, 314–321.
Ludvigsen, S., Cress, U., Rosé, C. P., Law, N., & Stahl, G. (2018). Developing understanding beyond the given knowledge and new methodologies for analyses in CSCL. *International Journal of Computer-Supported Collaborative Learning, 13*(4), 359–364.
Mäkitalo-Siegl, K., Kohnle, C., & Fischer, F. (2011). Computer-supported collaborative inquiry learning and classroom scripts: Effects on help-seeking processes and learning outcomes. *Learning and Instruction, 21*(2), 257–266.
McComas, J. J., Moore, T., Dahl, N., Hartman, E., Hoch, J., & Symons, F. (2009). Calculating contingencies in natural environments: Issues in the application of sequential analysis. *Journal of Applied Behavior Analysis, 42*(2), 413–423.
Mercer, N. (2008). The seeds of time: Why classroom dialogue needs a temporal analysis. *Journal of the Learning Sciences, 17*(1), 33–59.
Neuendorf, K. A. (2002). *The content analysis: Guidebook* (1st ed.). Thousand Oaks, CA: Sage Publications.
Oner, D. (2013). Analyzing group coordination when solving geometry problems with dynamic geometry software. *International Journal of Computer-Supported Collaborative Learning, 8*(1), 13–39.
Pedaste, M., Mäeots, M., Siiman, L. A., de Jong, T., van Riesen, S. A. N., Kamp, E. T., et al. (2015). Phases of inquiry-based learning: Definitions and the inquiry cycle. *Educational Research Review, 14*, 47–61.
Pohl, M., Wallner, G., & Kriglstein, S. (2016). Using lag-sequential analysis for understanding interaction sequences in visualizations. *International Journal of Human-Computer Studies, 96*, 54–66.
Popov, V., van Leeuwen, A., & Buis, S. C. A. (2017). Are you with me or not? Temporal synchronicity and transactivity during CSCL. *Journal of Computer Assisted Learning, 33*(5), 424–442.
Quintana, C., Reiser, B. J., Davis, E. A., Krajcik, J., Fretz, E., Duncan, R. G., et al. (2004). A scaffolding design framework for software to support science inquiry. *Journal of the Learning Sciences, 13*(3), 337–386.
Raes, A., Schellens, T., De Wever, B., & Vanderhoven, E. (2012). Scaffolding information problem solving in web-based collaborative inquiry learning. *Computers & Education, 59*(1), 82–94.
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.
Reimann, P. (2009). Time is precious: Variable- and event-centred approaches to process analysis in CSCL research. *International Journal of Computer-Supported Collaborative Learning, 4*(3), 239–257.
Roll, I., Butler, D., Yee, N., Welsh, A., Perez, S., Briseno, A., et al. (2018). Understanding the impact of guiding inquiry: The relationship between directive support, student attributes, and transfer of knowledge, attitudes, and behaviours in inquiry learning. *Instructional Science, 46*(1), 77–104.
Saab, N., van Joolingen, W., & van Hout-Wolters, B. (2012). Support of the collaborative inquiry learning process: Influence of support on task and team regulation. *Metacognition and Learning, 7*(1), 7–23.
Sharma, P., & Hannafin, M. J. (2007). Scaffolding in technology-enhanced learning environments. *Interactive Learning Environments, 15*(1), 27–46.
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.
Sobocinski, M., Malmberg, J., & Järvelä, S. (2017). Exploring temporal sequences of regulatory phases and associated interactions in low- and high-challenge collaborative learning sessions. *Metacognition and Learning, 12*(2), 275–294.
Stahl, G. (2017). Group practices: A new way of viewing CSCL. *International Journal of Computer-Supported Collaborative Learning, 12*(1), 113–126.
Tawfik, A. A., Giabbanelli, P. J., Hogan, M., Msilu, F., Gill, A., & York, C. S. (2018). Effects of success v failure cases on learner-learner interaction. *Computers & Education, 118*, 120–132.
Veerman, A. L., Andriessen, J. E. B., & Kanselaar, G. (2000). Learning through synchronous electronic discussion. *Computers & Education, 34*(3), 269–290.
Vogel, F., Wecker, C., Kollar, I., & Fischer, F. (2017). Socio-cognitive scaffolding with computer-supported collaboration scripts: A meta-analysis. *Educational Psychology Review, 29*(3), 477–511.
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.
Wang, X., Kollar, I., & Stegmann, K. (2017). Adaptable scripting to foster regulation processes and skills in computer-supported collaborative learning. *International Journal of Computer-Supported Collaborative Learning, 12*(2), 153–172.
Wise, A. F., & Chiu, M. (2011). Analyzing temporal patterns of knowledge construction in a role-based online discussion. *International Journal of Computer-Supported Collaborative Learning, 6*(3), 445–470.
Wise, A. F., & Schwarz, B. B. (2017). Visions of CSCL: Eight provocations for the future of the field. *International Journal of Computer-Supported Collaborative Learning, 12*(4), 423–467.
Wood, D., Bruner, J. S., & Ross, G. (1976). The role of tutoring in problem solving. *Journal of Child Psychology and Psychiatry, 17*(2), 89–100.
Wu, S. (2019). Incorporation of collaborative problem solving and cognitive tools to improve higher cognitive processing in online discussion environments. *Journal of educational computing research*Advance online publication. online version https://doi.org/10.1177/0735633119828044.
Yang, X., Li, J., & Xing, B. (2018). Behavioral patterns of knowledge construction in online cooperative translation activities. *The Internet and Higher Education, 36*, 13–21.
Yücel, Ü. A., & Usluel, Y. K. (2016). Knowledge building and the quantity, content and quality of the interaction and participation of students in an online collaborative learning environment. *Computers & Education, 97*, 31–48.
Zhang, S., Liu, Q., Chen, W., Wang, Q., & Huang, Z. (2017). Interactive networks and social knowledge construction behavioral patterns in primary school teachers' online collaborative learning activities. *Computers & Education, 104*, 1–17.
Zion, M. (2008). On line forums as a 'rescue net' in an open inquiry process. *International Journal of Science and Mathematics Education, 6*(2), 351–375.
Zion, M., Michalsky, T., & Mevarech, Z. R. (2005). The effects of metacognitive instruction embedded within an asynchronous learning network on scientific inquiry skills. *International Journal of Science Education, 27*(8), 957–983.

Abbreviations

CIBL: collaborative inquiry-based learning
IBL: inquiry-based learning
LSA: lag sequential analysis
TEL: technology-enhanced learning
TLDA: temporal log data analysis
TLSA: temporal lag sequential analysis

Appendix A

Table A.1. Coding manual based on the phases of inquiry-based learning.

Phase	Description	Example episode	Comment
Orientation	- Stimulating interest in and curiosity about the problem. - Identifying the main concepts of the assignment. - Becoming familiar with technological resources.	Ville: 'What does the [Python] program look like?' Leena: 'Let's run the [Python] program, as there is no need to make any modifications to it.' Paavo: 'Yeah, that's true. Running . . . A path emerged.' Ville: 'It looks like a protein sequence. The output is a bit silly.'	Group is becoming familiar with the Python program and its output.
Conceptualisation	- Proposing research questions or hypotheses. - Determining the dependent and independent variables that are needed to solve the problem.	Ville: 'If it [the total displacement] is proportional to *t* [time], then it will always move in the same direction, won't it?'	Ville proposes a hypothesis that connects the dependent variable [the total displacement] and the independent variable [time].
Investigation	- Planning data collection. - Exploring, collecting, analysing and interpreting data.	Paavo: 'How does the [total] displacement depend on time? Let's see, this [the number of collisions] is 50. And this [atom] almost moved to its [original] position. When it goes longer . . . The more often it moves . . . If I input 10 times longer, for example, or five times [changing the value of the number of collisions] . . .'. Leena: 'Is it [the total displacement] proportional to *t* [time], to the square root of *t* or to *t* squared?' Paavo: 'Now it already moves 15 units.'	Paavo collects data with the Python program by running the program with a different value of the number of collisions.
Conclusion	- Offering and evaluating solutions to the research questions and hypotheses.	Satu: 'Is that a square root [of time]?' Ville: 'I would believe so.'	Satu offers a solution, (i.e., the total displacement is proportional to the square root of time), which Ville accepts.
Discussion	- Communicating and elaborating findings and conclusions. - Reflecting either the entire IBL process after its completion or a single phase of the IBL process in real-time.	Ville: 'I am already prepared to answer it [the total displacement is proportional to the square root of time].' Satu: 'It cannot be. . . . It cannot be that proportional [to time].' Ville: 'That would mean that it [the atom] practically moves in the same direction all the time.' Leena: 'Yeah.' Satu: 'It cannot be.'	The group communicates and then elaborates upon their conclusions by excluding one of the options, i.e., the total displacement cannot be proportional to time.

Appendix B

Table B.1. The results of the follow-up groups based on the log data

Group index	Scaffold	Solution to the problem	Time (min)	Number of runs (Python program)	Number of runs with the same value of number of collisions
1	No	correct	22.1	18	2.6
2	No	wrong	17.6	4	1.3
3	No	correct	16.3	9	1.5
4	No	correct	15.5	6	1.2
5	Writing	correct	41.0	9	1.3
6	Writing	wrong	19.0	12	1.5
7	Writing	correct	30.0	6	1.2
8	Script	correct	17.6	3	1
9	Script	correct	17.3	6	1
10	Script	wrong	34.5	22	1.6
11	Script	wrong	20.1	13	1.6

Appendix C

Table C.1. Standardized residuals (z-scores) of the IBL transition patterns in non-scaffolded condition.

	Lag 1	**Orientation**	**Conceptualisation**	**Investigation**	**Conclusion**	**Discussion**
Lag 0	**Orientation**	3.55***	-0.56	0.17	-0.4	-2.33
	Conceptualisation	-0.88	1.53	0.84	-1.52	-0.29
	Investigation	-0.78	1.92	-2.38	1.6	0.47
	Conclusion	-1.7	-0.69	-1.01	-0.18	2.93**
	Discussion	-0.59	-2.11	2.16*	0.06	-0.05

*** $p < 0.001$ ** $p < 0.01$ * $p < 0.05$

Table C.2. Yule's Q values of the IBL transition patterns in non-scaffolded condition (the value -1 indicates that the frequency of the observed transitions is zero).

	Lag 1	**Orientation**	**Conceptualisation**	**Investigation**	**Conclusion**	**Discussion**
Lag 0	**Orientation**	0.67	-0.18	0.04	-0.16	-0.56
	Conceptualisation	-0.32	0.5	0.21	-1	-0.08
	Investigation	-0.21	0.43	-0.54	0.43	0.09
	Conclusion	-1	-0.35	-0.37	-0.1	0.69
	Discussion	-0.15	-0.64	0.4	0.02	-0.01

Table C.3. Averaged (relative) points (0 = start; 1 = end) in which the IBL transition patterns took place in non-scaffolded condition.

	Lag 1	**Orientation**	**Conceptualisation**	**Investigation**	**Conclusion**	**Discussion**
Lag 0	**Orientation**	0.11	0.27	0.35	0.76	0.26
	Conceptualisation	0.20	0.42	0.57	NA	0.51
	Investigation	0.47	0.45	0.27	0.86	0.51
	Conclusion	NA	0.87	0.80	0.59	0.79
	Discussion	0.42	0.53	0.55	0.69	0.78

Table C.4. Standardized residuals (*z*-scores) of the IBL transition patterns in writing scaffolded condition.

	Lag 1	**Orientation**	**Conceptualisation**	**Investigation**	**Conclusion**	**Discussion**
Lag 0	**Orientation**	1.01	0.43	0.07	-1.39	-0.44
	Conceptualisation	-1.79	2.17*	0.53	0.48	-0.18
	Investigation	-1.39	0.48	-1.07	0.06	1.97*
	Conclusion	-1.9	0.59	-0.43	-0.9	2.31*
	Discussion	2.21*	-2.23	0.9	1.48	-2.52

*** $p < 0.001$ ** $p < 0.01$ * $p < 0.05$

Table C.5. Yule's Q values of the IBL transition patterns in writing scaffolded condition (the value -1 indicates that the frequency of the observed transitions is zero).

	Lag 1	**Orientation**	**Conceptualisation**	**Investigation**	**Conclusion**	**Discussion**
Lag 0	**Orientation**	0.2	0.16	0.01	-0.6	-0.08
	Conceptualisation	-1	0.76	0.19	0.26	-0.07
	Investigation	-0.31	0.17	-0.23	0.02	0.35
	Conclusion	-1	0.31	-0.17	-1	0.64
	Discussion	0.39	-1	0.17	0.42	-0.44

Table C.6. Averaged (relative) points (0 = start; 1 = end) in which the IBL transition patterns took place in writing scaffolded condition.

	Lag 1	**Orientation**	**Conceptualisation**	**Investigation**	**Conclusion**	**Discussion**
Lag 0	**Orientation**	0.17	0.34	0.34	0.65	0.44
	Conceptualisation	NA	0.47	0.37	0.76	0.66
	Investigation	0.42	0.60	0.62	0.87	0.61
	Conclusion	NA	0.75	0.90	NA	0.87
	Discussion	0.40	NA	0.71	0.91	0.60

Table C.7. Standardized residuals (*z*-scores) of the IBL transition patterns in script scaffolded condition.

	Lag 1	**Orientation**	**Conceptualisation**	**Investigation**	**Conclusion**	**Discussion**
Lag 0	**Orientation**	2.98**	0.72	-0.98	-0.56	-1.41
	Conceptualisation	0.06	-1.1	1.1	-0.33	-0.23
	Investigation	-2.31	0.37	1.45	-0.93	0.8
	Conclusion	-1.14	-1.28	-1.46	1.02	2.31*
	Discussion	0.54	0.56	-0.28	0.85	-1.03

*** $p < 0.001$ ** $p < 0.01$ * $p < 0.05$

Table C.8. Yule's Q values of the IBL transition patterns in script scaffolded condition (the value -1 indicates that the frequency of the observed transitions is zero).

	Lag 1	**Orientation**	**Conceptualisation**	**Investigation**	**Conclusion**	**Discussion**
Lag 0	**Orientation**	0.61	0.25	-0.26	-0.22	-0.34
	Conceptualisation	0.02	-1	0.32	-0.17	-0.07
	Investigation	-0.67	0.12	0.28	-0.3	0.15
	Conclusion	-0.52	-1	-0.5	0.34	0.54
	Discussion	0.13	0.17	-0.05	0.22	-0.19

Table C.9. Averaged (relative) points (0 = start; 1 = end) in which the IBL transition patterns took place in script scaffolded condition.

	Lag 1	**Orientation**	**Conceptualisation**	**Investigation**	**Conclusion**	**Discussion**
Lag 0	**Orientation**	0.28	0.49	0.37	0.60	0.16
	Conceptualisation	0.48	NA	0.45	0.63	0.56
	Investigation	0.47	0.48	0.53	0.73	0.50
	Conclusion	0.35	NA	0.56	0.72	0.79
	Discussion	0.29	0.48	0.54	0.74	0.56