Chapter 12
Multimodal Measures Characterizing Collaborative Groups' Interaction and Engagement in Learning

Jonna Malmberg, Eetu Haataja, Tiina Törmänen, Hanna Järvenoja, Kateryna Zabolotna, and Sanna Järvelä

Abstract In this chapter, we outline how modes of interaction, such as cognitive and socio-emotional, and the regulation of learning provide support for collaborative engagement and examine how it changes over time. We start by framing how regulated learning is embedded in the cognitive and socio-emotional interaction between the group members from both a theoretical and a methodological perspective. We then move to illustrate, with an empirical case example, how multimodal data (i.e., video) and physiological signals, such as electrodermal activity indicating physiological synchrony between the group members, can be used to capture varying levels of collaborative engagement. The empirical example provides a complementary view on group interaction and collaborative engagement. We conclude by discussing how investigating group interaction that targets regulation can reveal how collaborative engagement is built and maintained. Additionally, we discuss future possibilities to harness multimodal data in practice to support collaborative engagement.

1 Introduction

Today, engagement is viewed as a multidimensional construct that involves behavioural, cognitive, and social forms, including self-regulated learning (SRL) (Cleary & Zimmerman, 2012; Fredricks et al., 2004). In the context of collaborative learning, these constructs are complementary to each other and are manifested through cognitive and socio-emotional interactions between collaborating learners. The concept of collaborative engagement builds on the self-regulated learning (SRL)

J. Malmberg (✉) · E. Haataja · T. Törmänen · H. Järvenoja · K. Zabolotna · S. Järvelä
Department of Educational Sciences and Teacher Education, Learning and Educational Technology Research Unit (LET), University of Oulu, Oulu, Finland
e-mail: jonna.malmberg@oulu.fi; eetu.haataja@oulu.fi; tiina.tormanen@oulu.fi; hanna.jarvenoja@oulu.fi; kateryna.zabolotna@oulu.fi; sanna.jarvela@oulu.fi

V. Kovanovic et al. (eds.), *Unobtrusive Observations of Learning in Digital Environments*, Advances in Analytics for Learning and Teaching,
https://doi.org/10.1007/978-3-031-30992-2_12

theoretical framework (Winne & Hadwin, 1998), because it allows to consider engagement as a dynamic process through which students participate in and maintain their engagement in collaboration over time (Cleary & Zimmerman, 2012). To conclude, extending the concept of collaborative engagement allows us to consider it as a process, and examine how its behavioural, cognitive and social facets change and build collaborative engagement over time, instead of considering it as an unchangeable inclusive state.

Socio-emotional and cognitive interaction involves collaborative and responsive interactions between group members (Isohätälä et al., 2017). Thus, we highlight how observable and covert forms of engagement are best understood within the social context, task and situation in which they occur (Cleary & Zimmerman, 2012). In collaborative learning, the key property of engagement is the interactional synchrony associated with the regulation of learning that occurs between individuals (Järvelä et al., 2016). A high degree of synchrony indicates a high level of collaborative engagement. In this chapter, we demonstrate how facets of engagement vary, including measures of physiological synchrony measured from the electrodermal activity (EDA) of the collaborating students. In empirical research, physiological synchrony has been shown to be informative and aligned with social interactions (Mønster et al., 2016) and aligned with the level of engagement (Hernandez et al., 2014; Khosa & Volet, 2014). Due to the rapid evolution of technology, educational research has begun to investigate new avenues to explore and augment theories of learning with novel technologies (Reimann & Bannert, 2017).

The large number of technological advancements in the field of education provides novel opportunities to explore collaborative engagement with unobtrusive multimodal data (Baker & Siemens, 2014) and consequently provides new viewpoints for collaborative learning and regulated learning research. Over the past few years, there has been an increasing interest in collecting multimodal data in the context of collaborative learning (Noroozi et al., 2020). Specifically, recent advances in combining multiple data channels (such as physiological data, log data, video recordings including gestures and utterances, and facial expressions) have made it possible to locate invisible markers of learner interactions, including regulated learning in the learning context (Malmberg et al., 2019a).

In the context of collaborative learning, the regulated learning process is a nuanced phenomenon that includes various representations in terms of cognitive and socio-emotional interactions (Järvelä et al., 2020). Contemporary research suggests gathering data from multiple sources can add to understanding of collaborative engagement and how it is shaped by regulation of learning (Azevedo, 2015; Lee et al., 2019). As well as the visible indicators, regulation of learning is influenced by physiological indicators such as stress, excitement, enthusiasm, or emotional dynamics (Mønster et al., 2016). Being able to capture these various multimodal representations in learning allows for richer understandings of how the learning process is regulated as it occurs. The power of multimodal data in SRL research lies in this capability to provide constitutive explanations that combine different modalities to unpack, for example, how sequences of different reactions and events change learners' regulated learning behaviour (Reimann, 2009).

In this chapter, we start by framing how regulated learning is embedded in the cognitive and socio-emotional interaction between group members from both theoretical and methodological perspectives. We then move to illustrate, with an empirical case example, how multimodal data, namely videos and electrodermal activity (EDA), can be used to capture varying levels of collaborative engagement. The empirical example provides complementary views on group interaction and collaborative engagement. We conclude by discussing how investigating cognitive and socio-emotional interactions, including regulated learning, can reveal how collaborative engagement is built and maintained within groups.

1.1 Engagement in Collaborative Learning

Collaborative learning is a complex combination of all learners' contributions to a groups' collective effort, reciprocal interactions, and joint attention (Barron, 2003). Learners in collaborative groups share information, search for joint solutions to the task and sustain a shared understanding of the task (Iiskala et al., 2011; Zabolotna et al., 2023). To engage in collaborative learning and achieve joint learning goals, learners must continuously monitor their learning and that of their group members' cognitive and socio-emotional interactions. Interaction among group members affects the quality and effectiveness of collaborative learning (e.g., Kuhn, 2015; Van den Bossche et al., 2006). Accordingly, collaborative learning requires learners' engagement and participation in joint activities towards a shared goal (Hadwin et al., 2018).

However, collaborative learning is seldom easy (Barron, 2003; Van den Bossche et al., 2006). Learners face socio-emotional or cognitive challenges that require them to recognize and externalize the challenges for their group members and engage in regulated learning (Hadwin et al., 2018). In the context of collaborative learning, socially shared regulation of learning (SSRL) and co-regulation of learning (CoRl) have been the main theoretical framework for understanding how students can overcome challenges in their engaged learning (Hadwin et al., 2018). Co-regulated learning (CoRL) occurs when learners' regulatory activities are guided, supported, shaped, or constrained by other members in the group (Hadwin & Oshige, 2011). Miller and Hadwin (2015) specified that in the context of collaborative learning, CoRL can take at least two forms. In the first form, CoRL occurs when group members prompt each other to contribute to the group. This happens, for example, when some group members prompt their peers to set learning goals that can be shared with the group. In the second form, CoRL occurs when an individual's SRL is gradually influenced by others. This means, for example, that other group members adapt their group members' learning goals but do not contribute to or co-construct learning goals together.

Socially shared regulation of learning (SSRL) emerges when group members work together to complement and negotiate shared perceptions and goals for the task. The group members then coordinate strategic enactments of the joint task, collectively monitor the group's progress and products, and make changes when needed to optimize collaboration in and across tasks (Hadwin & Oshige, 2011; Winne & Hadwin, 1998). In particular, the core of SSRL is the participation in transactive and reciprocal interactions, referring to the ways learners intentionally engage with and build upon each other's regulatory acts to solve cognitive or socio-emotional challenges in collaborative learning. This is to say, SSRL is embedded in cognitive and socio-emotional interactions. When learners engage in such interactions, they evaluate each other's contributions, justify and express their own opinions and ideas and provide answers to posed questions (Molenaar et al., 2011). This means that during the collaboration, students' interaction is not focused only on knowledge co-construction but also involves CoRL and SSRL embedded in cognitive and socio-emotional interactions that cannot be separated, especially in collaborative engagement (Järvelä et al., 2016).

1.2 Cognitive and Socio-Emotional Interaction Reflecting Students' Engagement in Collaborative Learning

Participation in interaction is the core mechanism facilitating collaborative engagement. It allows students to construct a shared conception of a problem (Roschelle & Teasley, 1995) and maintain the social and emotional conditions needed to keep the task progressing. In the collaborative learning literature, a distinction between cognitive and socio-emotional types of interactions is often made (Järvelä et al., 2016; Kreijns et al., 2003). In this chapter, we demonstrate the relevance of these two types of interaction for students for regulated learning and collaborative engagement.

Cognitive interactions refer broadly to a task-focused exchange among group members (Dillenbourg et al., 1995; Järvelä et al., 2016). Cognitive interaction is the engine building students' shared conceptions of a problem as it involves elaboration on the content to be studied (Sinha et al., 2015). In addition to discussing the task content, collaboration involves interaction that targets students' own and their group members' thinking. This means that students' interactions during collaboration are not solely focused on the task content itself but also involve metacognitive monitoring (Artz & Armour-Thomas, 1992). For example, it is important that students metacognitively monitor their progress and express their views in their interactions with other group members (Hadwin et al., 2018; Sinha et al., 2015; Malmberg et al., 2017). When the group members agree on how they understand the problem and how they are progressing with it, it is also easier for them to control and decide together on the efficient use of strategies for solving the task. This type of active interplay between monitoring and control has also been considered to reflect cognitive engagement in collaborative learning (Sinha et al., 2015). Possibly, due to that, the quality of monitoring seen in student interaction is linked to high-quality engagement. Students' monitoring of their own and their peers' task progress, task understanding, and task interests seem to contribute to group success. This means that high-quality monitoring asks for active and equal contributions to the process of group monitoring (Rogat & Linnenbrink-Garcia, 2011), supporting the socially shared regulation of the learning. However, recent research has shown that in addition to cognitive engagement, collaborative learning is, to a great extent, reliant on effective socio-emotional interaction.

In collaborative learning, group members can engage in a socio-emotional interaction as an operation to build up and maintain purposeful interchanges between students to express and shape perceptions of emotions and the group's socio-emotional atmosphere (Kreijns et al., 2003; Mänty et al., 2020). The quality of socio-emotional interactions indicates group members' collaborative engagement, which involves responsive and respectful interactions as well as group cohesion (Sinha et al., 2015). Previous research has found that positive socio-emotional interactions can promote cognitive engagement by facilitating CoRL and SSRL (Lajoie et al., 2015; Rogat & Adams-Wiggins, 2015; Rogat & Linnenbrink-Garcia, 2011). In moments of off-task behaviour, positive socio-emotional interaction can also be used as a means of supporting group members' behavioural engagement and to help them return to joint learning activities (Sinha et al., 2015; Järvelä et al., 2021). In turn, negative socio-emotional interactions can hinder the quality of group learning activities and, consequently, cognitive collaborative learning processes (Rogat & Adams-Wiggins, 2015). Negative socio-emotional interactions during group learning can also result in group members' negative emotional experiences of collaboration (Mänty et al., 2020) and, thus, play a role in how they will engage in future tasks. However, when negative socio-emotional interactions are challenging the group's grounds for collaboration, the group can utilize emotion regulation to restore a positive emotional state and to foster social engagement (Järvenoja et al., 2019). Accordingly, socio-emotional interactions and group regulatory processes, in combination, form a basis for understanding students' collaborative engagement as well as how group members collectively construct and maintain positive socio-emotional grounds for learning together (Järvenoja et al., 2013).

2 Studying Cognitive and Socio-Emotional Interactions as Part of Collaborative Engagement with Multimodal Data

Research on collaborative engagement is challenging as it stands at the intersection of individual and social processes. It is also challenging to show how types of interactions change over time in real-life learning settings and how learners regulate their learning to maintain engaging collaboration (Khosa & Volet, 2014). Over the past few years, a range of innovative analytical approaches for examining and interpreting the dynamics of interactions and regulated learning in real-life contexts have emerged (Azevedo, 2015). Emphasis in the field has been increasingly placed on real-time unobtrusive measurements that capture the dynamics of interaction and regulation as a part of engaged collaboration (Azevedo et al., 2018; Järvelä et al., 2016).

Recent research increasingly explores how multimodal data can be used to capture students' collaborative engagement and regulation of learning (Järvelä et al., 2020). This is because recent technological advancements have made it possible to utilize more data channels dealing with capturing cognitive and socio-emotional interactions within learning processes. Multimodal data is highly promising for collaborative learning research as it provides the potential to explain how self-regulation operates when learners engage with content. It can also extend our understanding on how collaborative engagement evolves over time in response to changes in situated conditions, and to present it as a function of changes in learners' level of engagement (Callan & Cleary, 2017).

Azevedo (2015) discusses how engagement can be detected by using unobtrusive multimodal data that capture cognitive, affective, metacognitive and motivational processes. Additionally, Azevedo (2015) evaluates how, and to what extent, different data channels (e.g., video data, log files, eye-tracking data and physiological sensors that capture EDA) are suitable for capturing engagement. Utilizing video recordings and physiological sensors is especially promising in the context of collaborative learning as it allows for the observation of participation in socio-emotional and cognitive interactions without interrupting students' learning process (Järvelä et al., 2019). This is because video data can provide continuous information about students' participation in such interactions that also coincides with, for example, study choices, confusion and changes in engagement in a learning situation, which are almost impossible to capture otherwise (Henriques et al., 2013; Winne, 2010). In its turn, EDA can provide continuous data related to perceived task difficulty and emotional activation (e.g., Malmberg et al., 2022a, b; Pecchinenda & Smith, 1996; Tomaka et al., 1993; Törmänen et al., 2022a). For example, Hernandez et al. (2014) investigated children's engagement in a social interaction with an adult by measuring EDA aligned with video data. They found that the features of EDA, such as the level of arousal measured from EDA and physiological synchrony, are relevant in detecting engagement during social interactions when compared with researchers' ratings of engagement during those interactions. Similarly, Morrison et al. (2020) found that measures of EDA were higher for items that the participating students rated themselves as being more engaged in the learning activities. This is to say, multimodal data, and especially the use of EDA in alignment with other data sources, has the potential to reveal collaborative engagement.

2.1 *Socio-Emotional Interaction Facilitates the Emergence of Group-Level Regulation*

Previous research has indicated that group members' collaborative engagement, defined by their participation in socio-emotional interactions, can facilitate the emergence of group-level regulation in collaborative learning (Lajoie et al., 2015; Rogat & Adams-Wiggins, 2015; Rogat & Linnenbrink-Garcia, 2011). Previous studies focusing on socio-emotional interactions utilizing multimodal data, such as video and EDA, have evidenced that when socio-emotional atmosphere remains generally positive, group members are more likely to initiate regulation in the face of socio-emotional challenges. However, when negative socio-emotional interactions are recurring, the groups' ability to regulate their learning is hindered (Törmänen et al., 2022a). Moreover, by utilizing EDA data as an indicator of the groups' emotional activation, their results propose that the group's shared regulation efforts and subsequent changes in their emotional states or learning activities may be reflected as changes in the physiological activation level. In addition, earlier research has shown that if individual students' socio-emotional profiles are different, it is likely to promote SSRL in a group (Törmänen et al., 2022a). Törmänen et al. (2022a) investigated individual group members' socio-emotional interaction profiles across four collaborative learning sessions with a person-centred approach. The results reveal three types of student profiles (negative, neutral, diverse), which can also be used as indicators of their social engagement in their group's collaborative learning. Students with a diverse profile are more likely to participate in their group's positive socio-emotional interactions than those with negative and neutral profiles, which can be considered an indicator of their high social engagement in collaborative learning. Accordingly, students with a diverse profile are more likely to contribute to the group-level regulation.

2.2 Cognitive Interaction Supports the Function of Group-Level Regulation

Previous studies have acknowledged the importance of SSRL for active engagement in collaborative learning interactions (Isohätälä et al., 2017). It has also been established that high-quality cognitive engagement depends on consistent metacognitive monitoring focusing on progress at the task (Sinha et al., 2015). Recently, Haataja et al. (2022) have studied how metacognitive interaction focusing on planning, task interpretation, strategy use, and reflection, group-level regulation and individual metacognitive monitoring accurately predict learning achievement in a high school physics course. Their results showed that the frequency of observed metacognitive monitoring that triggered CoRL was related to better learning achievement. However, the relationship of observed co-regulation to learning achievement depended on metacognitive monitoring that triggered cognitive interaction. This result emphasizes the importance of active collaborative engagement between group members because, besides potentially having an effect of its own, it could be the preacquisition needed for effective group-level regulation to occur.

In addition, previous studies have shown that when a group shows cognitive engagement in relation to challenging situations, they also tend to activate and align physiologically (Malmberg et al., 2021; Haataja et al., 2021). To specify, for example, Haataja et al. (2022) investigated how cognitive interactions, and more specifically interactions with a function of monitoring a group's collaborative learning process, relate to physiological arousal and physiological synchrony derived from EDA. The results show that, on average, groups' physiological arousal increased, and physiological synchrony was higher when groups monitored that they are not approaching their goal. To summarize, it seems that EDA has a great potential to inform the invisible and mental forms of need for regulation that provides support for collaborative engagement (Di Lascio et al., 2018).

2.3 *Case Example – Analysis of Interactions in Engaged Collaboration*

The case example illustrates what and how multimodal data (such as video recordings capturing students' collaborative interactions and EDA measuring their physiological synchrony) can indicate about students' collaborative engagement and regulation in collaborative learning.

2.3.1 Data Collection

The case example derives from the study design of secondary school students (~13 years of age, $N = 94$, 36 male, 58 female) from similar socio-economic backgrounds from a comprehensive school in an urban area of Northern Finland. The participating students were divided into 30 heterogeneous groups based on their previous science grade.

The study was conducted at the natural school settings as a part of their physics course. The students participated in the research when they were collaboratively learning about wave motion and its various physical manifestations during a 7-week study period. The collaborative tasks were designed together between the science teachers and researchers. The science teachers ensured that the topics covered the required subjects and contents, and the researchers ensured that tasks promoted regulation of learning and required genuine collaboration. The topics of the lessons and collaborative tasks focused on sound and light, light and vision, lenses, and reflection. For example, when studying reflection, the students were asked to use different types of lenses and make hypothesizes how the of beam of light would pass through different types of lenses and examine that in doing real experiments with the lenses. Each lesson followed the principles of the flipped classroom approach, due to its potential to facilitate the regulation of learning (Jovanović et al., 2019).

During their physics course the students were instructed to wear the Shimmer3 GSR (Burns et al., 2010) sensors independently to measure their EDA at the beginning of each physics lesson; they were informed that they could be taken off if they were uncomfortable. The lesson started with a short teacher-led instruction to ensure that students were familiar with the topic. This was followed by the collaborative learning tasks aimed to co-construct a more profound and shared understanding of the topic. The students' collaboration was also video recorded.

2.3.2 Analysis Protocol

The analysis proceeded in three phases. In phase 1, video data were coded to identify socio-emotional and cognitive interaction episodes. In phase 2, co-regulation and SSRL were identified from the coded socio-emotional and cognitive interaction episodes. In phase 3, physiological synchrony was observed from the EDA of each group member.

Phase 1. Locating Socio-Emotional and Cognitive Interactions from the Video Data First, *socio-emotional interaction* was coded in the 30-s segment when group members took verbal or behavioural actions related to socio-emotional or cognitive aspects of group formation and group dynamics, including expression of one's own emotions (Kreijns et al., 2003; Kwon et al., 2014). The code required interaction, which was defined as a reciprocal verbal exchange between two or more group members.

Socio-emotional interaction was coded when at least two group members showed clear verbal or visible bodily indicators of positive or negative emotions or engaged in negatively or positively charged interactions.

The coding scheme for cognitive interaction was developed and adjusted based on earlier coding scheme systems by Järvelä et al. (2016) and Whitebread et al. (2009). The first criterion to identify cognitive interaction was for students to engage in a task-focused interaction. The second criterion required at least two students to be involved in this interaction.

Phase 2. Locating Group-Level Regulation The second round of coding identified CoRL and SSRL from the coded socio-emotional and cognitive interaction episodes (Haataja et al., 2022). What differentiated these codes from socio-emotional and cognitive interaction was that students had to clearly express observation of an obstacle or a challenge in the learning process and, also, initiate regulation, which led to strategic changes in the groups' actions (Törmänen et al., 2022b). In CoRL, no additional response from other group members followed the initiation of regulation. In contrast, SSRL involved the reciprocal negotiated participation of several group members, leading to a strategic change in the learning process.

Phase 3. Measuring Physiological Synchrony Physiological synchrony reveals interdependence in physiology between the individuals in the group. The phasic signal component of EDA was used as the signal for calculation (Mendes, 2009). To calculate physiological synchrony, multidimensional recurrence quantification analysis (MdRQA) was used to quantify the physiological synchrony between the students.

3 Building Collaborative Engagement in Group Interaction – A Multimodal Data Case Example

Next, we present a case example that describes the first collaborative learning session from a group consisting of three female students (Linda, Maria and Rita). The case group was selected because it showed frequent cognitive and socio-emotional interactions, as well as mostly on-task behaviour. Further, in the first collaborative learning session, this group had frequent episodes of co- and socially shared regulation, which enabled the detailed exploration of these interaction processes in relation to each other. The case example aims to demonstrate the interplay between cognitive interaction, socio-emotional interaction, and regulation of learning, as well as their different functions in fostering group members' collaborative engagement. Further, the example uses physiological synchrony between the group members as a potential indicator of their collaborative engagement in the learning activity.

Figure 12.1 demonstrates the general flow of the physics lesson. During their collaboration, the group performed six subtasks (Task 1-Task 6) related to sound transmission which was the topic of the physics lesson. However, due to the nature of lesson structure, the teacher's instructions and organization of group work is not included in the description. As visualized in Fig. 12.1, the group showed cognitive interaction frequently throughout the session. They used cognitive interaction at the beginning of each subtask to form a shared task understanding, which they were also able to update while progressing with the tasks. Further, they used cognitive interaction frequently to metacognitively monitor their progress and reflect on their shared understanding of the phenomenon, which can be considered to signal collaborative engagement. In turn, the group used positive socio-emotional interaction, particularly during the first two subtasks, to build up a positive socio-emotional atmosphere for their collaboration, but also later to maintain a positive emotional state in the face of challenges and to promote the group members' social engagement. That is, the group showed high collaborative engagement throughout the learning process The case description shows how cognitive and socio-emotional interaction indicate students' collaborative engagement, but also set the stage for group-level regulation in the face of challenges.

Task 1: Mug Phone (0:39:00–0:50:00)

Building premises for collaborative engagement through cognitive and socio-emotional interaction.
0:39:00–0:43:30

The group starts a task on building and testing a mug phone. First, they start cognitive interaction on how to build the mug phone, which builds up cognitive engagement. After building the phone, they engage in positive socio-emotional interaction by laughing and having fun with the mug phone, which creates a positive emotional state for the group as a premise for their social engagement.

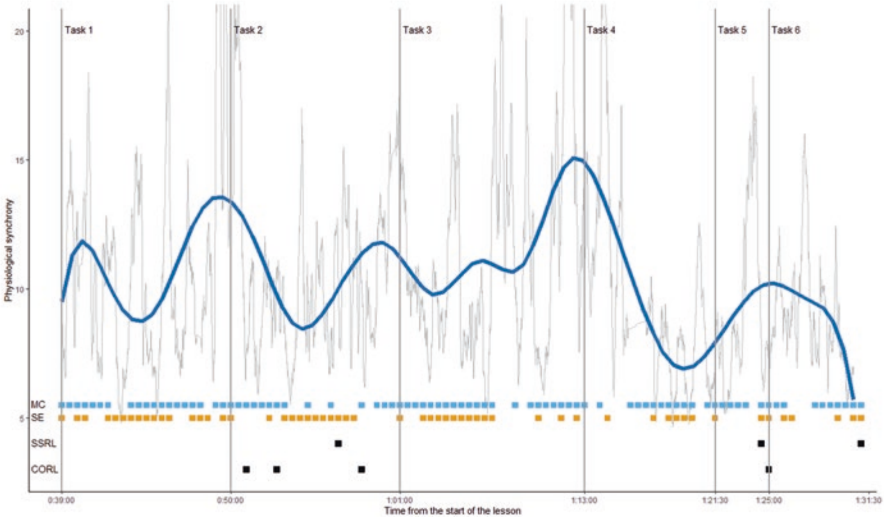

Fig. 12.1 Timeline of the case group demonstrating the occurrence of types of interactions and regulation along with physiological synchrony. Light blue marks cognitive interaction, orange marks socio-emotional interaction and black socially shared regulation and co-regulation. The blue line presents the trend of physiological synchrony of the group derived from the grey moving window MdRQA recurrence rate index

Moving towards the shared solution – physiological synchrony as a marker of collaborative engagement.
0:43:30–0:50:00

The group returns to the task instructions and, through cognitive interactions, builds a shared understanding of how they must explore the transmission of sound with the mug phone. Then, they start to execute the task together, discuss their findings, and agree on the answers they write down, showing a high cognitive engagement. Interestingly, while the group is moving towards the shared solution, the physiological synchrony between the group members starts to increase (0:45:00–0:49:30), potentially indicating the group members shared collaborative engagement in the learning activity.

Task 2: Church Bells (0:50:00–1:01:00)

Reorganizing for the new task – Decrease in physiological synchrony during individual activities.
0:50:00–0:51:00

The group starts a new task called "church bells," where they must explore the transmission of sound in a thread tied to a teaspoon. The group starts to prepare for the new task. Rita leaves the table to return the previous task equipment and the others start to foster social engagement through positive socio-emotional interaction towards the topic of the next task. Linda starts to joke ("Let's make the church bells!

I want to build the church bells. I have always dreamed of it!") and Maria joins ("Yay!"). Then, Linda and Maria start cognitive interaction and read the task out loud to form a shared task understanding. Rita returns to the table, but Linda and Maria leave to pick up the new task equipment. The group members perform different activities to prepare for the task, which seems to also be reflected in their physiological synchrony, which starts to decrease. Then, the group continues cognitive interaction together, aiming to form a shared understanding of the task by reading the instructions and discussing what they need to do in practice.

Engaged but not as a whole group.
0:51:00–0:53:30

Cognitive interaction in the group seems to prompt Linda to tell the others that she does not understand the task ("What do we need to do?") Maria responds by initiating co-regulation. She starts to tell Linda what she needs to do to perform the task. Linda and Maria start to explore the sound transmission together. However, Rita withdraws from the shared learning activity and starts to write down her notes individually. After a while, Linda and Maria face a cognitive challenge as they cannot hear the teaspoon through the thread. Linda uses positive socio-emotional interaction to maintain a positive emotional state in the face of the challenge and jokes that maybe they just have bad hearing. In turn, Maria starts cognitive interaction by considering the reasons why they cannot hear the sound ("What on earth? Why can't we hear the sound?"). Prompted by the metacognitive monitoring, Maria initiates co-regulation and suggests alternative strategies for the task execution, which Linda and Maria start to try.

Back in sync – having fun while learning as a whole group.
0:53:30–0:57:00

While still struggling with the task, Linda jokes again to maintain the positive emotional state ("We need to try all the pens available!") Finally, Linda and Maria succeed in the task and continue positive socio-emotional interaction, which supports Rita's behavioural engagement. Rita moves her attention back to the joint task execution and starts to make suggestions. When Rita returns to the joint activity, the physiological synchrony between the group members starts to increase again, along with the group members' collaborative engagement. To maintain Rita's behavioural engagement in the task, Linda and Maria ask Rita to try hearing the teaspoon and Linda continues positive socio-emotional interaction ("This is so fun, isn't it?") Then, the group continues the task execution together.

"*This is so fun*" – *Maintaining collaborative engagement through socio-emotional interaction and regulation while reaching solution.*
0:57:00–1:01:00

Linda and Maria start socially shared emotion regulation (Linda: "This is so, so fun!" Maria: "Yes, it is! We have so many observations related to this!"), promoting the group's social engagement in the task execution. The group continues task execution simultaneously, showing social engagement by having socio-emotional interaction on how the task is so fun. In addition to positive socio-emotional interaction, Linda uses co-regulation to ensure Rita's behavioural engagement with the task by asking if Rita has already written down some of their findings. Co-regulation prompts Rita to share her notes and the group starts cognitive interaction on how they can make sense of their findings and writes down their answers. The group reaches a solution and moves to the next task.

Task 3: Tuning Fork (1:01:00–1:13:00)

Moving to the next task – untuned again.
1:01:00–1:05:00

The group starts the third task: exploring the sound and wave motion with a tuning fork and water. First, they start cognitive interaction on task understanding. However, Maria and Rita leave to pick up the task equipment. Again, individual preparation activities seem to be reflected in a decrease in group members' physiological synchrony.

Increasing collaborative engagement through frequent cognitive and socio-emotional interaction.
1:05:00–1:13:00

The group has all the equipment ready, and they start enacting the task. They continuously engage in cognitive interaction to reflect their understanding of the phenomenon in light of their observations and findings showing high cognitive interaction. Further, they maintain social engagement through positive socio-emotional interactions (e.g., Linda: "This is so cool!") After the exploration, the group starts to discuss their shared answers. Along with the group members' increasing collaborative engagement in the task execution, their physiological synchrony seems to increase again while the group moves towards the task solution.

Task 4: Sound Volume (1:13:00–1:21:30)

Coordinating activity through cognitive interaction – No collaborative effort needed.
1:13:00–1:21:30

The group starts the next task: to categorize different sources of sound based on the volume. The nature of the learning activity changes from exploratory tasks to more traditional ones, where answers can be found in the textbook. In this task, the group members neither prepare together nor discuss how to proceed. Instead, Linda takes a lead and tells the others how she is going to do the task. The group follows Linda's lead, and they start to find the answers in their textbooks. The group stays coordinated in their learning activity through cognitive interaction and discusses the answers to form a shared understanding. Still, based on the decrease in group members' physiological synchrony, this task seems to be less optimal in fostering the collaborative engagement of the group. However, when the group decides to finalize the task, the physiological synchrony starts to increase again.

Task 5: How Deep Is the Lake? (1:21:30–1:25:00)

"*Just calculations*" – *Cognitive interaction.*
1:21:30–1:24:30

The group prepares shortly for the next task by cognitively interacting with and reading the task instructions out loud. The task is about calculating the depth of a lake based on the depth sounder information provided in the task instructions.

"We have certainly reached our goal" – Monitoring the progress with a positive tone.
1:24:30–1:25:00

After finding the correct answer for the task, Linda engages in cognitive interaction and monitors the group's progress by stating that they have almost performed all the tasks and they have only one task left. This initiates socially shared regulation in the group. First, Linda continues by monitoring that the group has certainly reached its goal. Rita then contributes by praising the group for completing all the tasks very thoroughly, simultaneously promoting collaborative engagement within the group. During this task, the group members' physiological synchrony increases again towards the end of the task.

Task 6: Transmission of Sound in Railways (1:25:00–1:31:30)

"*…are you ready for the last task*?" – *Co-regulating collaborative engagement.*
1:25:00–1:31:00

The last task starts when Linda promotes Maria's and Rita's behavioural engagement by co-regulation ("OK, are you ready for the last task?"). Linda is building up social engagement for the last task by initiating socio-emotional interaction by joking that she is an interviewer and starts to read the task out loud. This prompts, again, cognitive interaction within the group. The group starts to form a shared task understanding by reading the task together, and they also draw a picture of the calculation to increase their understanding. However, the teacher concludes the lesson, which interrupts the groups' task understanding phase.

Collaboratively engaged in reflection – building the foundations for next lesson.
1:31:00–1:31:30

Finally, after finishing their collaboration, the group shows cognitive engagement and starts socially shared regulation to reflect their goal achievement. Meanwhile, they maintain social engagement with positive socio-emotional interaction on how the lesson was so fun. Reflecting both, cognitive and socio-emotional aspects with a positive tone may set a fruitful foundation for the group's future lessons.

4 Practical Implications and Future Potential of the Research Reviewed

With the case example, we demonstrated the strengths and weaknesses that different data channels hold for characterizing interaction and engagement in collaborative learning. Regarding collaborative engagement and the different types of interactions that constitute it, i.e., cognitive and socio-emotional, video data offers invaluable evidence of the occurrence of these types of interactions that show how students engage in collaboration. Physiological data complements the observations and offers an affirmation that reduced collaborative engagement of a group is also reflected in decreased physiological synchrony. This means that when students are working individually with the task, physiological synchrony decreases. In contrast, highly engaging episodes seem to co-occur with cognitive and socio-emotional interaction visible in the video, in addition to increase in physiological synchrony.

A growing body of empirical research has demonstrated that when a group has frequent cognitive interactions throughout their learning process, it has the potential to support the function of group-level regulation as well (Haataja et al., 2022; Khosa & Volet, 2014). In turn, when group members participate in socio-emotional interactions, they are more likely to contribute to their group's regulation of learning (Törmänen et al., 2022a). Moreover, frequent positive socio-emotional interaction, in general, has the potential to foster the emergence of group-level regulation in the face of challenges (Bakhtiar et al., 2018; Törmänen et al., 2022b). The findings of these earlier empirical studies show the function of cognitive and socio-emotional interaction for group-level regulation but do not, however, reveal how they intertwine and are realized in actual collaborative interaction. The detailed case example made visible how individual contributions for regulation, cognitive- and socio-emotional interactions promote each other, exist in parallel and function equally, without any subordinate relationship in either direction. Yet, we still lack systematic empirical research showing how cognitive- and socio-emotional interaction both foster group-level regulation that provides support for collaborative engagement. The case examples illustrate how collaborative engagement is built and maintained temporally and is guided by the situational conditions. This is to say, engagement is not an enduring state, but is rather shaped in collaborative interaction.

Video data is a valuable source for understanding the qualities of interaction. What we can see and hear provides contextual information on how collaborative engagement is built up in a learning situation. However, video analysis is highly time-consuming and labour-intensive, even when systematic approaches are applied (Malmberg et al., 2019a, b; Zabolotna et al., 2023). Nevertheless, video data is still needed to fully understand the situated nature of collaborative engagement (Järvenoja et al., 2015). It makes concrete and visible the moments of physiological synchrony, when all group members contribute to task execution through cognitive and socio-emotional interactions and reveals how collaborative engagement is manifested in a situation. One way, perhaps, to speed up the laborious video-analysis could be to explore the potential of speech recognition (e.g., frequency of individual contributions) aligned with physiological synchrony (Noroozi et al., 2019). Combining speech recognition and data resulting from EDA with traditional video observations could potentially reveal the moments of collaborative engagement, but this requires further examination.

Yet, the question arises of whether and to what extent EDA can be used to measure collaborative engagement. Since EDA reflects the general level of physiological arousal, it remains a debatable question whether such data and i.e., indices of physiological synchrony on their own can offer much information about the state of collaborative engagement and regulation. This is to say, EDA should not be treated as the final authoritative data source for studying engagement, but rather used as a complementary method. Combining it with traditional video-based analyses is a good example of how learning processes can be examined from different perspectives by using multiple data sources. There may be a potential for future artificial intelligence (AI) technologies to help expedite such work. The reliability and appropriate use of AI-based technologies will also depend on what and how generic data are used to develop them and to what extent they can be applied in varying learning tasks. However, the current chapter provides an interesting viewpoint on the possible ways to explore collaborative engagement with the existing unobtrusive methods.

Acknowledgements Blinded.

References

Artz, A. F., & Armour-Thomas, E. (1992). Development of a cognitive-metacognitive framework for protocol analysis of mathematical problem solving in small groups. *Cognition and Instruction, 9*(2), 137–175. https://doi.org/10.1207/s1532690xci0902_3

Azevedo, R. (2015). Defining and measuring engagement and learning in science: Conceptual, theoretical, methodological, and analytical issues. *Educational Psychologist, 50*(1), 84–94. https://doi.org/10.1080/00461520.2015.1004069

Azevedo, R., Taub, M., & Mudrick, N. V. (2018). Understanding and reasoning about real-time cognitive, affective, and metacognitive processes to foster self-regulation with advanced learning technologies. In D. H. Schunk & J. A. Greene (Eds.), *Handbook of self-regulation of learning and performance* (2nd ed., pp. 254–270). Routledge. https://doi.org/10.4324/9781315697048

Baker, R., & Siemens, G. (2014). Educational data mining and learning analytics. In R. K. Sawyer (Ed.), *The Cambridge handbook of the learning sciences* (2nd ed., pp. 253–272). Cambridge University Press. https://doi.org/10.1017/CBO9781139519526.016

Bakhtiar, A., Webster, E. A., & Hadwin, A. F. (2018). Regulation and socio-emotional interactions in a positive and a negative group climate. *Metacognition and Learning, 13*(2), 57–90. https://doi.org/10.1007/s11409-017-9178-x

Barron, B. (2003). When smart groups fail. *Journal of the Learning Sciences, 12*(3), 307–359. https://doi.org/10.1207/S15327809JLS1203_1

Burns, A., Doheny, E. P., Greene, B. R., Foran, T., Leahy, D., O'Donovan, K., & McGrath, M. J. (2010). SHIMMER: An extensible platform for physiological signal capture. In *2010 annual international conference of the IEEE Engineering in Medicine and Biology Society (EMBC)*, pp. 3759–3762. https://doi.org/10.1109/IEMBS.2010.5627535

Callan, G. L., & Cleary, T. J. (2017). Multidimensional assessment of self-regulated learning with middle school math students. *School Psychology Quarterly, 33*(1), 103–111. https://doi.org/10.1037/spq0000198

Molenaar, I., Chiu, M. M., Sleegers, P., & van Boxtel, C. (2011). Scaffolding of small groups' metacognitive activities with an avatar. *International Journal of Computer-supported Collaborative Learning, 6*, 601–624.

Cleary, T. J., & Zimmerman, B. J. (2012). A cyclical self-regulatory account of student engagement: Theoretical foundations and applications. In S. L. Christenson, A. L. Reschly, & C. Wylie (Eds.), *Handbook of research on student engagement* (pp. 237–257). Springer. https://doi.org/10.1007/978-1-4614-2018-7_11

Di Lascio, E., Gashi, S., & Santini, S. (2018). Unobtrusive assessment of students' emotional engagement during lectures using electrodermal activity sensors. *Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies, 2*(3), 1–21.

Dillenbourg, P., Baker, M. J., Blaye, A., & O'Malley, C. (1995). The evolution of research on collaborative learning. In E. Spada & P. Reimann (Eds.), *Learning in humans and machine: Towards an interdisciplinary learning science* (pp. 189–211). Elsevier.

Fredricks, J. A., Blumenfeld, P. C., & Paris, A. H. (2004). School engagement: Potential of the concept, state of the evidence. *Review of Educational Research, 74*(1), 59–109. https://doi.org/10.3102/00346543074001059

Haataja, E., Malmberg, J., Dindar, M., & Järvelä, S. (2021). The pivotal role of monitoring for collaborative problem solving seen in interaction, performance, and interpersonal physiology. *Metacognition and Learning, 17*(1), 241–268. https://doi.org/10.1007/s11409-021-09279-3

Haataja, E., Dindar, M., Malmberg, J., & Järvelä, S. (2022). Individuals in a group: Metacognitive and regulatory predictors of learning achievement in collaborative learning. *Learning and Individual Differences, 96*, 102146. https://doi.org/10.1016/j.lindif.2022.102146

Hadwin, A. F., Järvelä, S., & Miller, M. (2018). Self-regulation, co-regulation, and shared regulation in collaborative learning environments. In D. H. Schunk & J. A. Greene (Eds.), *Handbook of self-regulation of learning and performance* (pp. 83–106). Routledge.

Hadwin, A., & Oshige, M. (2011). Self-regulation, coregulation, and socially shared regulation: Exploring perspectives of social in selfregulated learning theory. *Teachers College Record, 113*(2), 240–264.

Henriques, R., Paiva, A., & Antunes, C. (2013). On the need of new methods to mine electrodermal activity in emotion-centered studies. In L. Cao, Y. Zeng, A. L. Symeonidis, V. I. Gorodetsky, P. S. Yu, & M. P. Singh (Eds.), *ADMI 2012: Agents and data mining interaction* (pp. 203–215). Springer. https://doi.org/10.1007/978-3-642-36288-0_18

Hernandez, J., Riobo, I., Rozga, A., Abowd, G. D., & Picard, R. W. (2014). Using electrodermal activity to recognize ease of management in children during social interactions. In *UbiComp'14: Proceedings of the 2014 ACM international joint conference on pervasive and ubiquitous computing*, pp. 307–317. https://doi.org/10.1145/2632048.2636065

Iiskala, T., Vauras, M., Lehtinen, E., & Salonen, P. (2011). Socially shared metacognition of dyads of pupils in collaborative mathematical problem-solving processes. *Learning and Instruction, 21*(3), 379–393. https://doi.org/10.1016/j.learninstruc.2010.05.002

Isohätälä, J., Järvenoja, H., & Järvelä, S. (2017). Socially shared regulation of learning and participation in social interaction in collaborative learning. *International Journal of Educational Research, 81*, 11–24. https://doi.org/10.1016/j.ijer.2016.10.006

Järvelä, S., Järvenoja, H., Malmberg, J., Isohätälä, J., & Sobocinski, M. (2016). How do types of interaction and phases of self-regulated learning set a stage for collaborative engagement? *Learning and Instruction, 43*, 39–51. https://doi.org/10.1016/j.learninstruc.2016.01.005

Järvelä, S., Gašević, D., Seppänen, T., Pechenizkiy, M., & Kirschner, P. A. (2020). Bridging learning sciences, machine learning and affective computing for understanding cognition and affect in collaborative learning. *British Journal of Educational Technology, 51*(6), 2391–2406.

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 Iournal of Computer-supported Collaborative Learning*, 425–441.

Järvelä, S., Malmberg, J., Haataja, E., Sobocinski, M., & Kirschner, P. A. (2021). What multimodal data can tell us about the students' regulation of their learning process?. *Learning and Instruction, 72*, 101203.

Järvenoja, H., Järvelä, S., & Malmberg, J. (2015). Understanding regulated learning in situative and contextual frameworks. *Educational Psychologist, 50*(3), 204–219.

Järvenoja, H., Näykki, P., & Törmänen, T. (2019). Emotional regulation in collaborative learning: When do higher education students activate group level regulation in the face of challenges?. *Studies in Higher Education, 44*(10), 1747–1757.

Järvenoja, H., Volet, S., & Järvelä, S. (2013). Regulation of emotions in socially challenging learning situations: An instrument to measure the adaptive and social nature of the regulation process. *Educational Psychology, 33*(1), 31–58.

Jovanović, J., Mirriahi, N., Gašević, D., Dawson, S., & Pardo, A. (2019). Predictive power of regularity of pre-class activities in a flipped classroom. *Computers & Education, 134*, 156–168. https://doi.org/10.1016/j.compedu.2019.02.011

Khosa, D. K., & Volet, S. E. (2014). Productive group engagement in cognitive activity and metacognitive regulation during collaborative learning: Can it explain differences in students' conceptual understanding?. *Metacognition and Learning, 9*, 287–307. https://doi.org/10.1007/s11409-014-9117-z

Kreijns, K., Kirschner, P. A., & Jochems, W. (2003). Identifying the pitfalls for social interaction in computer-supported collaborative learning environments: A review of the research. *Computers in Human Behavior, 19*(3), 335–353. https://doi.org/10.1016/S0747-5632(02)00057-2

Kuhn, D. (2015). Thinking together and alone. *Educational Researcher, 44*(1), 46–53. https://doi.org/10.3102/0013189X15569530

Kwon, K., Kim, E. M., & Sheridan, S. M. (2014). The role of beliefs about the importance of social skills in elementary children's social behaviors and school attitudes. *Child & Youth Care Forum, 43*, 455–467. https://doi.org/10.1007/s10566-014-9247-0

Lajoie, S. P., Lee, L., Poitras, E., Bassiri, M., Kazemitabar, M., Cruz-Panesso, I., Hmelo-Silver, C., Wiseman, J., Chan, L. K., & Lu, J. (2015). The role of regulation in medical student learning in small groups: Regulating oneself and others' learning and emotions. *Computers in Human Behavior, 52*, 601–616. https://doi.org/10.1016/j.chb.2014.11.073

Lee, V. R., Fischback, L., & Cain, R. (2019). A wearables-based approach to detect and identify momentary engagement in afterschool Makerspace programs. *Contemporary Educational Psychology, 59*, 101789. https://doi.org/10.1016/j.cedpsych.2019.101789

Malmberg, J., Järvelä, S., & Järvenoja, H. (2017). Capturing temporal and sequential patterns of self-, co-, and socially shared regulation in the context of collaborative learning. *Contemporary Educational Psychology, 49*, 160–174.

Malmberg, J., Järvelä, S., Holappa, J., Haataja, E., Huang, X., & Siipo, A. (2019a). Going beyond what is visible: What multichannel data can reveal about interaction in the context of collaborative learning?. *Computers in Human Behavior, 96*, 235–245.

Malmberg, J., Haataja, E., Seppänen, T., & Järvelä, S. (2019b). 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*, 467–490.

Malmberg, J., Fincham, O., Pijeira-Díaz, H. J., Järvelä, S., & Gašević, D. (2021). Revealing the hidden structure of physiological states during metacognitive monitoring in collaborative learning. *Journal of Computer Assisted Learning, 37*(3), 861–874.

Malmberg, J., Saqr, M., Järvenoja, H., & Järvelä, S. (2022a). How the monitoring events of individual students are associated with phases of regulation: A network analysis approach. *Journal of Learning Analytics, 9*(1), 77–92.

Malmberg, J., Haataja, E., & Järvelä, S. (2022b). Exploring the connection between task difficulty, task perceptions, physiological arousal and learning outcomes in collaborative learning situations. *Metacognition and Learning, 17*(3), 793–811.

Mänty, K., Järvenoja, H., & Törmänen, T. (2020). Socio-emotional interaction in collaborative learning: Combining individual emotional experiences and group-level emotion regulation. *International Journal of Educational Research, 102*, 101589. https://doi.org/10.1016/j.ijer.2020.101589

Mendes, W. B. (2009). Assessing autonomic nervous system activity. In E. Harmon-Jones & J. S. Beer (Eds.), *Methods in social neuroscience* (pp. 118–147). Guilford.

Miller, M., & Hadwin, A. (2015). Scripting and awareness tools for regulating collaborative learning: Changing the landscape of support in CSCL. *Computers in Human Behavior, 52*, 573–588.

Mønster, D., Håkonsson, D. D., Eskildsen, J. K., & Wallot, S. (2016). Physiological evidence of interpersonal dynamics in a cooperative production task. *Physiology & Behavior, 156*, 24–34. https://doi.org/10.1016/j.physbeh.2016.01.004

Morrison, A. L., Rozak, S., Gold, A. U., & Kay, J. E. (2020). Quantifying student engagement in learning about climate change using galvanic hand sensors in a controlled educational setting. *Climatic Change, 159*, 17–36. https://doi.org/10.1007/s10584-019-02576-6

Noroozi, O., Alikhani, I., Järvelä, S., Kirschner, P., Juuso, I., & Seppänen, T. (2019). Multimodal data to design visual learning analytics for understanding regulation of learning. *Computers in Human Behavior, 100*, 298–304. https://doi.org/10.1016/j.chb.2018.12.019

Noroozi, O., Pijeira-Díaz, H., Sobocinski, M., Dindar, M., Järvelä, S., & Kirschner, P. A. (2020). Multimodal data indicators for capturing cognitive, motivational, and emotional learning processes: A systematic literature review. *Education and Information Technologies, 25*, 5499–5547. https://doi.org/10.1007/s10639-020-10229-w

Pecchinenda, A., & Smith, C. A. (1996). The affective significance of skin conductance activity during a difficult problem-solving task. *Cognition and Emotion, 10*(5), 481–503. https://doi.org/10.1080/026999396380123

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*, 239–257.

Reimann, P., & Bannert, M. (2017). Self-regulation of learning and performance in computer-supported collaborative learning environments. In *Handbook of self-regulation of learning and performance* (pp. 285–303). Routledge

Rogat, T. K., & Adams-Wiggins, K. R. (2015). Interrelation between regulatory and socio-emotional processes within collaborative groups characterized by facilitative and directive other-regulation. *Computers in Human Behavior, 52*, 589–600. https://doi.org/10.1016/j.chb.2015.01.026

Rogat, T. K., & Linnenbrink-Garcia, L. (2011). Socially shared regulation in collaborative groups: An analysis of the interplay between quality of social regulation and group processes. *Cognition and Instruction, 29*(4), 375–415. https://doi.org/10.1080/07370008.2011.607930

Roschelle, J., & Teasley, S. D. (1995). The construction of shared knowledge in collaborative problem solving. In C. O'Malley (Ed.), *Computer supported collaborative learning* (pp. 69–97). Springer. https://doi.org/10.1007/978-3-642-85098-1_5

Sinha, S., Rogat, T. K., Adams-Wiggins, K. R., & Hmelo-Silver, C. E. (2015). Collaborative group engagement in a computer-supported inquiry learning environment. *International Journal of Computer-Supported Collaborative Learning, 10*(3), 273–307. https://doi.org/10.1007/s11412-015-9218-y

Tomaka, J., Blascovich, J., Kelsey, R. M., & Leitten, C. L. (1993). Subjective, physiological, and behavioral effects of threat and challenge appraisal. *Journal of Personality and Social Psychology, 65*(2), 248–260. https://doi.org/10.1037/0022-3514.65.2.248

Törmänen, T., Järvenoja, H., Saqr, M., Malmberg, J., & Järvelä, S. (2022a). A person-centered approach to study students' socio-emotional interaction profiles and regulation of collaborative learning. *Frontiers in Education, 7*, 866612. https://doi.org/10.3389/feduc.2022.866612

Törmänen, T., Järvenoja, H., Saqr, M., Malmberg, J., & Järvelä, S. (2022b). Affective states and regulation of learning during socio-emotional interactions in secondary school collaborative groups. *British Journal of Educational Psychology*, e12525. https://doi.org/10.1111/bjep.12525

Van den Bossche, P., Gijselaers, W. H., Segers, M., & Kirschner, P. A. (2006). Social and cognitive factors driving teamwork in collaborative learning environments: Team learning beliefs and behaviors. *Small Group Research, 37*(5), 490–521.

Whitebread, D., Coltman, P., Jameson, H., & Lander, R. (2009). Play, cognition and self-regulation: What exactly are children learning when they learn through play? *Educational and Child Psychology, 26*(2), 40–52.

Winne, P. H. (2010). Bootstrapping learner's self-regulated learning. *Psychological Test and Assessment Modeling, 52*(4), 472.

Winne, P. H., & Hadwin, A. F. (1998). Studying as self-regulated learning. In D. J. Hacker, J. Dunlosky, & A. C. Graesser (Eds.), *Metacognition in educational theory and practice* (pp. 277–304). Erlbaum.

Zabolotna, K., Malmberg, J., & Järvenoja, H. (2023). Examining the interplay of knowledge construction and group-level regulation in a computer-supported collaborative learning physics task. *Computers in Human Behavior, 138*, 107494. https://doi.org/10.1016/j.chb.2022.107494