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Elisa Vilhunen

Epistemic emotions in science learning situations

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Abstract

The purpose of this dissertation was to increase understanding about the role of students' situational epistemic emotions in authentic contexts of science education. Epistemic emotions are defined as emotions that have an object focus on knowledge or knowledge construction and are thus hypothesised to play a significant role in educational contexts. The first overall aim of the study was to examine the relationship between different instructional activities and students' experiences of epistemic emotions. The second aim was to investigate how such experiences relate to science learning among students.

This thesis comprises three original studies reporting research conducted in Finnish upper secondary level physics lessons. Study I examined the relationship between instructional activities and epistemic emotions by means of experience sampling and video observation. Experience sampling data on epistemic emotions was combined with students' pretest and posttest performance in Study II to investigate the relationship between epistemic emotions and science learning. Finally, Study III explored the entanglement of epistemic emotions and the development of students' scientific understanding during a computer-based predict-observe-explain activity in which data on their sensemaking processes was linked to their trajectories of situational epistemic emotions.

A variety of quantitative and qualitative methods were used, and two main empirical findings emerged. First, epistemic emotions can be aroused in a classroom context by instructional activities: orienting and engaging activities typically relate to positive emotions, and cognitively more demanding activities to emotions that are more negative. Second, epistemic emotions and science learning are intertwined: curiosity, excitement, confusion and surprise appear to be beneficial for learning, whereas boredom and frustration may be detrimental. Furthermore, it could be concluded that it is important to examine emotions on the situational level instead of using only retrospective measures. Overall, the findings underline the importance of epistemic emotions in the context of science education, and the complexity of the interplay between affective and cognitive factors.

Keywords: epistemic emotions, science learning, experience sampling method, upper secondary students

Helsingin yliopisto, Kasvatustieteellinen tiedekunta
Kasvatustieteellisiä tutkimuksia, numero 158

Elisa Vilhunen

Episteemiset tunteet luonnontieteiden oppimistilanteissa

Tiivistelmä

Tämän väitöstutkimuksen tarkoituksena oli lisätä ymmärrystä opiskelijoiden tilannekohtaisten episteemisten tunteiden roolista aidoissa luonnontieteiden opiskelun konteksteissa. Episteemisillä tunteilla tarkoitetaan tunteita, joiden kohteena on tieto tai tiedon muodostaminen, joten niiden voidaan olettaa olevan merkityksellisiä opiskelussa ja oppimisessa. Tutkimuksen yhtenä päätavoitteena oli selvittää luokkahuoneaktiviteettien ja opiskelijoiden episteemisten tunteiden välistä suhdetta. Toisena tavoitteena oli tutkia, miten opiskelijoiden kokemat episteemiset tunteet ovat yhteydessä heidän luonnontieteiden oppimiseen.

Työ koostuu kolmesta alkuperäistutkimuksesta, jotka on toteutettu lukion fysiikan oppitunneilla. Tutkimuksessa I opetus- ja opiskeluaktiviteettien yhteyttä opiskelijoiden episteemisiin tunteisiin selvitettiin kokemusotantamenetelmän ja videohavainnoinnin avulla. Tutkimuksessa II kokemusotanta-aineisto tunteista yhdistettiin opiskelijoiden esi- ja jälkitestituloksiin tunteiden ja oppimisen välisen suhteen selvittämiseksi. Tutkimuksessa III tutkittiin episteemisten tunteiden ja tieteellisen ymmärryksen kehittymisen yhteyttä tietokonepohjaisessa ”ennusta-havainnoi-selitä” -aktiviteetissa.

Useita määrällisiä ja laadullisia menetelmiä hyödyntäen tuloksista tehtiin kaksi pääjohtopäätöstä. Ensiksi opetuksellisin menetelmin voidaan vaikuttaa opiskelijoiden kokemiin episteemisiin tunteisiin luokkahuonetilanteissa: opiskeluun orientoivat ja motivoivat aktiviteetit liittyvät tyypillisesti positiivisiin episteemisiin tunteisiin, kun taas kognitiivisesti vaativammat aktiviteetit liittyvät tyypillisesti negatiivisiin episteemisiin tunteisiin. Toiseksi episteemiset tunteet ja luonnontieteen oppiminen kietoutuvat toisiinsa: uteliaisuus, innostus, hämmennys ja yllättyneisyys näyttäytyvät oppimisen kannalta hyödyllisinä, kun taas tylsistyminen ja turhautuminen voivat olla haitaksi oppimiselle. Lisäksi voidaan päätellä, että tunteita on tärkeää tutkia tilannetasolla sen sijaan, että käytettäisiin ainoastaan retrospektiiviä mittareita. Kaiken kaikkiaan tulokset korostavat episteemisten tunteiden tärkeyttä luonnontieteiden opetuksessa, sekä affektiivisten ja kognitiivisten tekijöiden välisen vuorovaikutuksen monimutkaisuutta.

Avainsanat: episteemiset tunteet, luonnontieteiden oppiminen, kokemusotantamenetelmä, lukio-opiskelijat

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Veikkola, 14.2.2023
Elisa Vilhunen

List of original articles

This dissertation is based on the following publications:

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II. Vilhunen, E., Turkkila, M., Lavonen, J., Salmela-Aro, K. & Juuti K. (2022). Clarifying the relation between epistemic emotions and learning by using experience sampling method and pre-posttest design. *Frontiers in Education, 7*(826852). https://doi.org/10.3389/feduc.2022.826852

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Contents

1 Introduction

Emotions are known to play an important role in academic contexts, and in many ways they are significant for learning (Pekrun et al., 2018; Pekrun & Linnenbrink-Garcia, 2014a; Sinatra et al., 2014). Among other things, they arouse interest (Schukajlow & Rakoczy, 2016), facilitate memorising (Gruber et al., 2014) and help to maintain motivation (Bjørnebekk, 2008; Kim & Pekrun, 2014), engagement (Schneider et al., 2016) and self-regulation (Reindl et al., 2020), or they may impede concentration (Tze et al., 2016) and make students give up (D'Mello & Graesser, 2012). The relationship between emotions and learning or academic performance has been addressed in numerous previous studies (e.g., Camacho-Morles et al., 2021; Efklides, 2017; Muis et al., 2015; Sainio et al., 2021).

Student enjoyment and motivation related to science has been decreasing in many Western countries in particular, and fewer adolescents pursue a career in fields related to science and engineering (Ainley & Ainley, 2011; OECD, 2016; Osborne & Dillon, 2008). Society, with its current challenges, needs people with high levels of scientific literacy. Thus, engaging students in learning science should be a mission for researchers, teachers and other practitioners.

Despite the growing body of literature on emotions in educational contexts, there has long been a need for studies on their role in authentic science learning contexts (Sinatra et al., 2014). Thus, the aim in the present thesis is to clarify the role of emotions in science education by exploring their contextual antecedents and their interplay with science learning in authentic classroom situations. In this thesis, the focus is on *epistemic* emotions, which refer to such emotions that have a stimulus or object focus on knowledge or knowledge construction (Pekrun et al., 2018).

This thesis comprises three interrelated sub-studies (herein referred to as Study I, Study II and Study III), all conducted among physics students in Finnish upper secondary schools. The focus in Study I (Vilhunen et al., 2021) is on the effect of instructional activities on students' epistemic emotions; Study II (Vilhunen, Turkkila, et al., 2022) examines the interrelation between epistemic emotions and learning; and Study III explores the entangled relationship between students' epistemic emotions and their ability to make sense of a scientific phenomenon (Vilhunen, Chiu, et al., 2022). Both qualitative and quantitative methods are used in addressing the research questions, as well as variable-oriented and person-oriented approaches (Bergman & Trost, 2006; Eye & Bogat, 2006).

1.1 What are emotions and why are they important?

Emotions are commonly defined as affective episodes that are caused by a certain stimulus or antecedent and have an object (Ekman, 1992; Russell, 2003; Shuman & Scherer, 2014). They therefore differ from moods and attitudes, which are typically more stable and long-lasting, and do not necessarily have such clear stimuli or an object. However, moods and attitudes may also play a role in educational contexts (Beege et al., 2018; Cahill et al., 2018). Moreover, even though emotions are conceptualised as affective states, individuals may have trait-like affective dispositions, in other words tendencies to experience certain emotions (Shuman & Scherer, 2014).

Emotions are reactions to some external or internal stimuli (Shuman & Scherer, 2014). Thus, they prepare individuals to react in an appropriate way to environmental factors. From a biological perspective, emotions could be described as adaptations that have developed in response to environmental factors, that is, to adaptive problems (Cosmides & Tooby, 2000). Throughout their evolutionary history, emotions have developed to enhance the chances of survival and reproduction among human populations. According to Cosmides and Tooby (2000), they resemble a superordinate programme that coordinates other components of human functions such as attention and perception, memory, motivations and goals, expressions, communication and behaviour, as well as information-processing and learning processes. The purpose of negative emotions has been to point out what is harmful or disadvantageous: fear warns of a danger to be avoided, for example. Correspondingly, positive emotions have helped in focusing on what is beneficial or advantageous. For example, feelings of affection help to maintain deep relationships, whereas curiosity and interest may facilitate learning and memorising. Emotions function in a similar way even nowadays, and help people to focus their attention on relevant issues: they give guidance in terms of avoiding what is appraised as disadvantageous, or engaging with what is appraised as advantageous. In an educational context, therefore, they could induce information-seeking or avoidance behaviour (Sharot & Sunstein, 2020). It thus seems evident that emotions have a role to play in studying and learning.

1.2 Emotions in educational contexts

Emotions are ubiquitous, meaning that they occur all the time and everywhere, educational contexts being no exception (Moeller et al., 2020; Pekrun et al., 2018). Emotions that arise in educational contexts, or that relate to learning, studying or other academic activities, are defined as academic emotions (Pekrun et al., 2002, 2018), and their significance in achievement, engagement and motivation is widely acknowledged (Pekrun et al., 2018; Schneider et al., 2020; Sinatra et al., 2014). Academic emotions are experienced during lessons, for example, as well as in the course of doing homework, preparing for or taking an exam or test, or engaging in independent or group work (Pekrun et al., 2018). In educational settings, they help students to adapt to events in the study environment. For example, stress or anxiety related to a forthcoming exam may raise the level of alertness in students and thus enable them to concentrate better. A difficult task may also cause confusion or frustration, for example, which could encourage students to seek an alternative way of doing the task, or then they might just give up. Learning may also evoke emotions of enjoyment or curiosity that could facilitate the acquisition of new knowledge.

Academic emotions can be further divided into four categories based on their stimulus or object of focus (Pekrun et al., 2018; Pekrun & Linnenbrink-Garcia, 2014a). First, *achievement emotions* such as joy or disappointment relate to success or attainment in academic tasks (Pekrun & Stephens, 2010). Second, *topic emotions* such as disgust or hopelessness have an object focus on the topics being studied (Lombardi & Sinatra, 2013). Third, *social emotions* such as a sense of belonging or inadequacy relate to social relationships in school, both between students and teachers and among peers (Anttila et al., 2018). Fourth and finally, *epistemic emotions* such as surprise or confusion relate to learning itself, and have an object focus on knowledge or knowledge construction (Pekrun et al., 2017). It is worth noting, however, that these four subcategories are not clean-cut or mutually exclusive (Pekrun & Linnenbrink-Garcia, 2014b). Depending on the stimulus or object of a certain emotion, it may represent various subcategories of academic emotions. For example, enjoyment attached to meeting a friend at school would be a social emotion, whereas enjoyment related to learning something new would be an epistemic emotion. Likewise, anxiety about a forthcoming exam is considered an achievement emotion, but anxiety aroused by cognitive incongruity would be an epistemic emotion.

It is also possible to categorise academic emotions, as all other emotions, based on their valence or arousal (Pekrun et al., 2002, 2018). Valence refers to pleasantness (i.e., positive vs. negative emotions) and arousal to the activating nature of the emotion (i.e., activating vs. deactivating). The circumplex model of emotions (Pekrun & Linnenbrink-Garcia, 2012; Russell, 1980) comprises four categories, namely positive activating emotions (e.g., enjoyment or pride), positive deactivating emotions (e.g., relief or contentment), negative activating emotions (e.g., anger or anxiety), and negative deactivating emotions (e.g., boredom or hopelessness).

1.3 Epistemic emotions

The word *epistemic* has its roots in the Ancient Greek word *epístamai*, which means to know or to understand. Epistemic emotions, in turn, have their stimuli in knowledge or knowledge construction, which makes them especially interesting in terms of learning, and in relation to educational practices. They typically arise in connection with contradictory or incongruous information whereby new comprehensions are developed (Pekrun et al., 2018; Pekrun & Linnenbrink-Garcia, 2012). Learning and understanding are cognitively demanding processes, thus they may evoke a variety of emotions.

Pekrun and colleagues (2017, 2018) classify surprise, enjoyment, curiosity, confusion, frustration, anxiety and boredom as epistemic emotions. According to the circumplex model of emotions (Pekrun & Linnenbrink-Garcia, 2012; Russell, 1980), enjoyment and curiosity could be considered positive activating emotions; confusion, frustration and anxiety negative activating emotions; and boredom a negative deactivating emotion. Surprise is an activating emotion, but depending on the context it may be experienced as positive, negative or neutral (Muis et al., 2015; Pekrun et al., 2017).

Epistemic emotions often occur simultaneously or in sequences (Bosch & D'Mello, 2017; Z. M. Han et al., 2021). Surprise is typically the primary emotion when one encounters novel or contradictory information (Chiu et al., 2014; D'Mello & Graesser, 2012; Theobald & Brod, 2021). This is often followed by confusion or curiosity, or both, in states of cognitive disequilibrium (D'Mello & Graesser, 2012). Deepening and persistent confusion may arouse feelings of anxiety or frustration in learning situations, which if prolonged could result in boredom and withdrawal. On the other hand, the removal of the cognitive discrepancy causing the confusion may again foster feelings of enjoyment and curiosity (Bosch & D'Mello, 2017; Pekrun et al., 2018). Thus, in learning situations, epistemic emotions may give rise to complex interplay between cognitive and affective factors.

According to the model put forward by Muis et al. (2015), cognitive incongruity arouses epistemic emotions, which influence learning outcomes through different learning strategies. Several other studies also point out this relationship. First, positive activating emotions of enjoyment (Ainley & Ainley, 2011; Camacho-Morles et al., 2021; Obergriesser & Stoeger, 2020; Pekrun et al., 2022; Putwain et al., 2018, 2021) and curiosity (Gruber et al., 2014; Gruber & Ranganath, 2019; Peterson & Hidi, 2019; Tang et al., 2022; Vogl et al., 2019, 2020; Wade & Kidd, 2019), in addition to surprise (Chiu et al., 2014; Muis et al., 2018; Vogl et al., 2019, 2020) and confusion (Arguel, Lockyer, Kennedy, et al., 2019; D'Mello et al., 2014; Muis et al., 2018; Vogl et al., 2019, 2020; Watkins et al., 2018), relate to positive learning outcomes through deep-processing learning strategies such as elaboration and critical thinking (Muis et al., 2015, 2021). On the other hand, it is also suggested that confusion is beneficial for learning only on appropriate levels, but if it goes unresolved it could even be detractive (Arguel, Lockyer, Chai, et al., 2019; Arguel, Lockyer, Kennedy, et al., 2019; D'Mello & Graesser, 2012; Lodge et al., 2018; Schneider et al., 2016).

Second, negative activating emotions such as anxiety (Ketonen & Lonka, 2012; Pekrun et al., 2022; Putwain et al., 2021) and frustration (Bosch & D'Mello, 2017; Richey et al., 2019) relate to negative learning outcomes through shallow processing strategies, such as maintenance rehearsal (Muis et al., 2015). Furthermore, a negative deactivating emotion such as boredom impairs the use of any learning strategies (Muis et al., 2015), thus also leading to negative learning outcomes (Camacho-Morles et al., 2021; Mann & Robinson, 2009; Pekrun et al., 2014, 2022; Putwain et al., 2018; Tze et al., 2016).

1.4 Science learning in the school context

Learning new knowledge and skills could be considered one of the fundamental aims of schooling and education. As Kansanen (2003) points out, learning in educational contexts could be seen as an end product of the teaching-studying-learning process. Hence, learning is preceded by studying, in other words the activities and efforts students make to achieve given learning goals. Similarly, studying is typically preceded by teaching, referring to teachers' activities aimed at motivating students to study and thereby to learn. Only the instructional part of the process can be controlled in the classroom context: teachers may guide students to study by means of teaching, but learning cannot be controlled directly. This relationship between teacher, student and content, reflecting the teaching-studying-learning process, emphasises the multifaceted nature of educational practices (Kansanen, 2003).

Further, learning could be defined as a process in which people acquire new skills, knowledge or understanding, whereas performance or achievement are more stationary constructs, merely reflecting the state of the learning process (Gross, 2015). Two general types of knowledge or learning have been distinguished, namely conceptual knowledge (knowing *that*) and procedural knowledge (knowing *how*) (OECD, 2019; Siegel, 1998). These are referred to in recent documents on science education policy as core disciplinary ideas and scientific practices, respectively (National Research Council, 2012). However, in the context of science learning they are frequently deeply intertwined in scientific sensemaking. Indeed, making sense of phenomena is characteristic of and pertinent to science learning, and is emphasised in research and curricular materials (L. Ding et al., 2021; Finnish National Board of Education, 2016; Krajcik, 2015; Kubsch et al., 2020; National Research Council, 2012; C. Schwarz et al., 2017). Odden and Russ (2019) define scientific sensemaking as "the process of building an explanation to resolve a perceived gap or conflict in knowledge" (p. 187). The ability to make sense of phenomena is essential for developing scientific understanding and advancing critical thinking.

Studying and teaching involve intentional activities aimed at learning, and in the school context these aims and goals are typically defined in curricula. Pertinent to the teaching and studying of science is the intertwinement of conceptual and procedural knowledge, as described above. This frequently manifests as inquiry learning and making sense of scientific phenomena. Thus, many instructional approaches in the context of science education aim at sensemaking. Project-based learning (PBL) is one example (Krajcik & Shin, 2014), whereby students construct knowledge and understanding of scientific phenomena by actively employing core disciplinary ideas as well as scientific and engineering practices.

Even if inquiry and experimentation are fundamental parts of science education, science lessons typically also include other activities, such as reviewing homework, teaching new content and independent classwork (Burns & Anderson, 1987; Mortimer & Scott, 2003). Thus, science lessons can provide versatile learning situations in which students can experience a variety of epistemic emotions.

1.5 Emotions and science learning

In the context of science education in particular, it has been noted that both positive and negative emotions typically relate to learning (Sinatra et al., 2014). The acquisition of scientific understanding tends to involve cognitively demanding activities, thereby arousing a variety of emotions among learners. Some people may find working on an interesting task or figuring out something new pleasant and enjoyable. According to findings from recent research in science inquiry, for example, generating predictions may include an element of surprise (Brod, 2021) and arouse curiosity (Brod & Breitwieser, 2019), thus engaging students in scientific sensemaking (Theobald & Brod, 2021). On the other hand, studying and learning new subject matter requires effort, which may also evoke negative emotions (Engle & Conant, 2002; Jaber & Hammer, 2016; Radoff et al., 2019) such as confusion or anxiety (Arguel, Lockyer, Chai, et al., 2019; Richey et al., 2019). Letting go of one's preconceptions and adopting new ones may be difficult and unpleasant. It has been found, for example, that cognitive load in inquiry activities (Hong et al., 2017) and prolonged incongruence in scientific modelling (M. Han & Gutierez, 2021) arouse negative emotions in students. Darner (2019) further argues that negative emotions could even lead to the denial of empirical evidence.

Indeed, in the context of science education, it has been suggested that negatively valenced emotions are integral to learning and engagement and inherent in science (Jaber & Hammer, 2016; Radoff et al., 2019). Since negative emotions are inevitable in learning, the so-called meta-affects (DeBellis & Goldin, 2006) appear as an important factor in science education contexts. Meta-affects facilitate enjoyment in learning situations that would otherwise be unpleasant. Emotion-aware teacher scaffolding can enable students to learn to experience negative epistemic emotions as pleasurable and as gateways to new realisations or achievements (Radoff et al., 2019). Thus, some researchers suggest that teachers should not try to minimise these negative emotions in the classroom, but rather support students in their experience of them as part of the learning process (DeBellis & Goldin, 2006; Jaber & Hammer, 2016). It is further argued that self-regulation of affects, or meta-affects, should be learned as part of the substance in science education (Jaber & Hammer, 2016).

To conclude, learning environments in science may differ fundamentally from the environments of some other school subjects. Engaging in scientific activities may arouse a particular set of epistemic emotions of which science teachers should also be aware (Davidson et al., 2020).

1.6 The present study

1.6.1 The perspective adopted

This dissertation contributes to the field of academic emotions and science education. The literature on emotions and science learning presented above provides a conceptual and theoretical framework to understand the associations between student emotions and science learning in general. Indeed, much is already known about the topic, but there are still challenges and gaps in the field that are addressed in this thesis.

First, despite the number of previous studies on academic emotions, there has been a lack of research on emotions in the context of science education (Sinatra et al., 2014). As noted above, learning contexts in science, including its characteristic epistemic practices, may differ from other learning contexts, implying a need to study epistemic emotions in subject-specific learning environments. Furthermore, there is a paucity of knowledge concerning the enhancement of beneficial emotions in practice, and little is known about how emotions relate to real (science) learning activities in classrooms (Meyer, 2014).

Second, there is a paucity of research conducted in ecologically valid, real-life classroom settings. Many studies based on situational measures of emotions have been conducted under relatively controlled, laboratory experimental conditions (Chiu et al., 2014; D'Mello et al., 2014; Gruber et al., 2014; Muis et al., 2015, 2018; Obergriesser & Stoeger, 2020; Wade & Kidd, 2019). Indeed, experimental laboratory studies may well provide detailed knowledge related to situational emotions and learning, but their ecological validity tends to be limited in that students' affective experiences in such settings may differ from the experiences in authentic classroom settings (Myin-Germeys & Kuppens, 2022). The arousal of emotions is typically manipulated in experimental settings, whereas real-life classroom situations are ought to arouse a more natural range of emotions in students. The studies comprising this dissertation were conducted in real-life science learning environments, in the context of upper secondary physics education. In the sub-studies, versatile science learning environments were employed, in which a variety of epistemic emotions were assumed to be aroused.

Third, given that emotions are, by nature, situational constructs they should be measured in real learning situations and not by means of retrospective questionnaires, for example (Goetz et al., 2016). However, many previous studies relied only on retrospective measures to examine emotions (Ainley & Ainley, 2011; Y. Ding & Zhao, 2020; D'Mello et al., 2014; Mann & Robinson, 2009; Pekrun et al., 2014; Sainio et al., 2019, 2021). The experience sampling method (ESM) was utilized in the studies comprising this dissertation to examine students' situational experiences of epistemic emotions.

Fourth, learning as a dynamic process, and conceptualised in textbooks as change in performance (Gross, 2015), cannot be studied cross-sectionally: consecutive measures should rather be used, or the learning process should be observed as a whole. Thus, despite the vast amount of research conducted on the association of emotions with learning-related variables, many previous studies have limitations in terms of relying only on cross-sectional measures of learning and performance (Bosch & D'Mello, 2017; Y. Ding & Zhao, 2020; Ketonen & Lonka, 2012; Mann & Robinson, 2009; Putwain et al., 2021). In this dissertation, learning was examined both through a pre-posttest design and in the course of an inquiry task as a scientific sensemaking process.

1.6.2 The aims of the thesis

Figure 1 below sets out the general aims of this thesis and the research questions addressed. The general aims addressed practical, theoretical, empirical and methodological issues. First, the practical aim was to enhance the knowledge and understanding of teachers and other practitioners in terms of how best to support science learning among students by acknowledging the role of emotions in the process. Second, the theoretical aim was to arrive at a deeper understanding of students' situational emotions in authentic contexts of science learning to strengthen the body of work in the field. Third, the empirical aim was to shed light on contextual factors related to students' epistemic emotions, as well as on the relationships between experienced epistemic emotions and science learning. Fourth, the methodological aim was to pinpoint the strong need for advanced, reliable and versatile methods to examine these relationships.

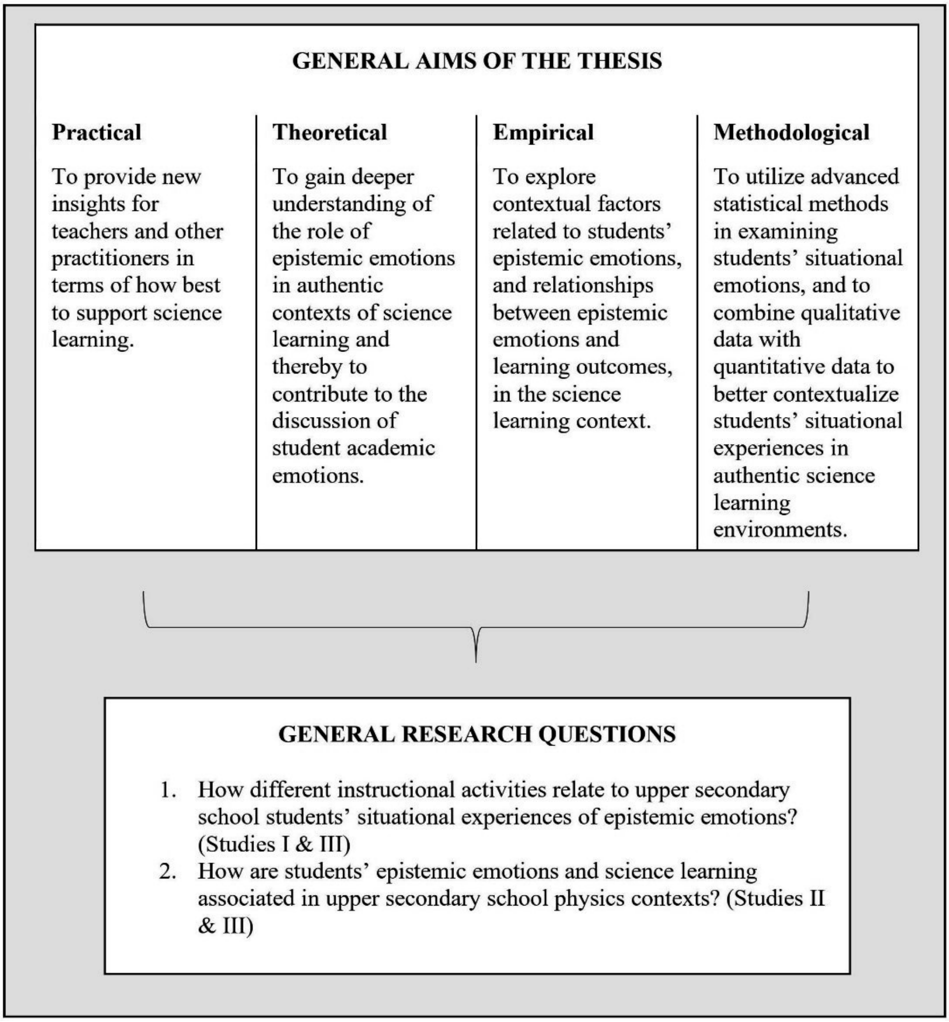

Figure 1. General aims and research questions

These four general aims resulted in three sub-studies addressing the two general research questions. The objective related to the first research question was to explore how different instructional activities in science lessons relate to students' epistemic emotions. This was considered in detail in Study I, in which instructional activities were analysed through video observation, and to a limited extent in Study II, which involved observation during different phases of a science inquiry task. The objective with the second research question was to find out how students' situational experiences of epistemic emotions relate to their science learning. This was addressed in Study II with its summative pre-posttest design, and in Study III with its focus on students' scientific sensemaking processes.

2 Methods

This chapter presents the context, the participants, the data collection procedures, the measures and the analytical approaches of the three sub-studies. It concludes with a methodological overview presented in Table 1. The methods are described only briefly here, and in more detail in the original publications.

Overall, this research represents the mixed-method approach, adopting a concurrent embedded strategy to examine the general research questions (Creswell, 2009). In other words, both quantitative and qualitative data were collected to address the different questions addressed in the three studies. However, quantitative methodology could be considered predominant, in which the qualitative approaches are embedded. The qualitative data is interpreted and quantified first to enable the quantitative examination of emotions and learning situations in the final phases of data analysis.

2.1 The research context: Finnish upper secondary science education

All three studies were conducted in the context of Finnish upper secondary education in physics. More precisely, data was collected during the first physics course at upper secondary school when the subject of the instruction was Newtonian mechanics (Finnish National Board of Education, 2016). This physics course is compulsory for all upper secondary students, most of which take it during their first year of upper secondary studies. They also have the choice of taking up to six optional physics courses. One of the general aims in the first course is to familiarise students with physics as a systematic and experimental natural science. They are also expected to learn the basics of force and motion.

Overall, the Finnish core curriculum for general upper secondary education emphasises active participation and knowledge generation in science. For example, observing scientific issues, interpreting data, explaining phenomena and drawing conclusions based on the evidence are characteristic for teaching and learning in science subjects (Finnish National Board of Education, 2016; Lavonen & Laaksonen, 2009). Within the Finnish education system, first-year students in upper secondary schools are typically 15 to 16 years old, and females are slightly overrepresented (58.2 % in 2019) (Official Statistics in Finland, 2020).

2.2 Experience sampling method (ESM)

ESM was used in the three studies to collect data on students' experiences of situational epistemic emotions (Goetz et al., 2016; Myin-Germeys & Kuppens, 2022; Zirkel et al., 2015). Larson and Csikszentmihalyi (2014) define ESM as a "research procedure for studying what people do, feel, and think during their daily lives" (p. 21). Experience sampling techniques are also sometimes referred to as ecological momentary assessment (Shiffman et al., 2008), ambulatory assessment (Trull & Ebner-Priemer, 2014), or the diary method (Iida et al., 2012). These methods have some fundamental benefits compared to more traditional data collection techniques such as using questionnaires or doing laboratory experiments. Although traditional questionnaire studies may provide valuable and solid evidence on the relations and variance of many constructs, they fall short in terms of giving information about behaviour *in situ* and within-person variance. Furthermore, retrospective questionnaires rely on the memory of participants, and are thus open to recall bias (Duckworth & Yeager, 2015). In addition, even if studies conducted under highly controlled, experimental laboratory conditions offer an important perspective on situational constructs, in terms of ecological validity they tend to be limited. ESM techniques, on the other hand, allow the capturing of moments in authentic settings, in real-time and on repeated occasions (Myin-Germeys & Kuppens, 2022). They are therefore useful in observations of behaviour or experiences that should be context- or situation-specific, as well as when the focus is on patterns of experiences within an individual.

The ESM data collection procedures used in Studies I and II were based on Schneider and colleagues' (2016) pioneering work in this field. An ESM questionnaire was delivered through mobile devices multiple times per lesson over a period of two-to-three weeks. The data for Study III, in turn, was collected during a single physics lesson, within a well-defined computer-based learning task. The questionnaire was integrated into the learning task and the students answered the questionnaire multiple times. However, in terms of design and data collection, the basic ESM principles and guidelines were followed.

2.3 Participants and data collection procedures

The datasets used in the three studies comprising this dissertation were collected within larger research projects: "PIRE: Crafting Optimal Learning in Science Environments" and "STEM: Engaging Learning Environments in STEM", funded by the Academy of Finland, and "Projektioppiminen: Oppilaiden sitoutuminen opiskeluun ja oppimisen arviointi digitaalisesti intensiivisessä lukion luonnontieteiden projektioppimisessa", funded by the Ministry of Education and Culture in Finland. The research was based on international collaboration with Michigan

State University (Schneider et al., 2016, 2020), but only data from Finnish classrooms is used in this dissertation. My involvement in the planning and implementation of the data collection dates back to 2018. The data for the three studies were collected from five Finnish upper secondary schools located in the Helsinki metropolitan area.

Study I was conducted during the school year 2019–2020 among five classes, and a total of 100 students from two schools took part. The data collection took place during a six-lesson (á 75 min) PBL study unit, in other words over a two-to-three-week period, during which the students' situational epistemic emotions were examined by means of ESM, delivered via smartphones. The lessons were also video-recorded to enable the observation of instructional activities.

Study II was conducted during autumn 2019 in six physics classes, the participants comprising a total of 148 students from two schools. The data collection took place during six or seven consecutive lessons. Students' epistemic emotions were measured through ESM in a similar way as in Study I. Furthermore, prior knowledge and learning outcomes in a study period were evaluated using a pre-posttest design. The pretest was conducted just before the study period began to measure the students' knowledge of the topic, and the posttest was given after the study period as part of the course exam, to measure learning outcomes.

Study III was conducted between autumn 2020 and spring 2021, again in six physics classes. A total of 113 students took part. The study design differed from that in Studies I and II, focusing only on a predetermined and well-defined inquiry learning situation. All the data on the students' epistemic emotions and scientific sensemaking were collected within a computer-based predict-observe-explain (POE) activity, during a single lesson. It took about 15 minutes for the students to complete the learning activity. The data were gathered as part of normal class work in four of the participating classes. However, the students in two of the classes completed the computer-based learning task at home in spring 2021, as part of distance learning due to the COVID-19 pandemic.

2.4 Measures

2.4.1 Epistemic emotions

Epistemic emotions (surprise, curiosity, enjoyment, confusion, anxiety, frustration and boredom) were measured in the studies using a modified single-item short version of The Epistemically-Related Emotion Scales (EES; Pekrun et al., 2017). Each item is measured on a five-point Likert scale in the original version, but in this case a four-point scale was used to avoid the mid-point option. The response categories ranged from 1 = "not at all" to 4 = "very much". The questionnaires were conducted in Finnish.

The student participants in Studies I and II were asked: "What do you think about the activity you did? Did you feel … surprised/curious/excited/confused/anxious/frustrated/bored?". It should be noted that according to the short version of EES, the emotion of enjoyment is measured in a single item of excitement (Pekrun et al., 2017). EES was implemented as part of the larger ESM questionnaire that included also other items on social, emotional and contextual aspects. Students responded to the ESM questionnaire three times per lesson. The study period for Study I covered six lessons, therefore each student had 18 opportunities to complete the questionnaire. Each student in Study II, on the other hand, had 18 or 21 opportunities to respond, depending on whether the teacher used six or seven lessons to cover the contents of Newtonian mechanics.

To keep the questionnaire as short and as easy to answer as possible, only four epistemic emotions were surveyed in Study III. In each questionnaire the students were asked: "How do you feel right now? Surprised/Curious/Confused/Bored". The epistemic emotions of surprise, curiosity and confusion were chosen, because they were expected to occur in this kind of an inquiry activity with contradictory and incongruous information. Boredom was included to represent a deactivating, negative epistemic emotion. The questionnaire included also some items reflecting other affective aspects. The EES was implemented within the computer-based three-cycle POE activity. After each POE situation, as part of the task, the students were asked to self-report their experiences of situational epistemic emotions. Epistemic emotions were also assessed at the beginning of the activity, as baseline measures. Thus, these emotions were reported four times in total.

2.4.2 Instructional activities

The question concerning the relationship between epistemic emotions and instructional activities in science lessons was addressed specifically in Study I, although Study III also provides insights into the contextual factors that evoke epistemic emotions. Instructional activities during the study period were examined in Study I through classroom video observations. Further, the video data was supplemented with corresponding lesson plans and stimulated recall interviews with the teachers of the learning units (Calderhead, 1981).

Study III was conducted within a computer-based POE activity. It therefore adds to current knowledge on the occurrence of epistemic emotions in such a well-defined inquiry activity, as well as on students' reactions to incongruent and contradictory information. Furthermore, the well-defined and relatively controlled setting allows for a more reliable examination of the longitudinal trajectories of emotions during the activity.

2.4.3 Science learning

Studies II and III addressed the research question on the relationship between epistemic emotions and science learning. A pre-posttest design was used in Study II to assess the students' knowledge of Newtonian mechanics. The same summative test served as both a pretest and a posttest. Performance in the former was conceptualised as prior knowledge, and in the latter as a learning outcome. The test included 13 questions on the core disciplinary ideas and the scientific practices related to force and motion phenomena, in other words the topics covered during the study period. The test was co-designed by researchers in science education and in-service physics teachers within the teacher-researcher partnership (Juuti et al., 2021; Schneider et al., 2020). The students had 30 minutes to complete each test (pretest and posttest). The test was conducted in Finnish, via a computer-based platform. The maximum score was 26. A researcher in the field of science education, who is also a qualified physics teacher, scored the tests.

In study III, students' science learning was examined through a scientific sensemaking process. In a computer-based POE activity students were introduced to three different situations concerning the motion of a falling object. The activity was conducted in Finnish. Assessment of the students' ability to make sense of the motion phenomenon was based on their written predictions, observations and explanations. During the three POE cycles the students were expected to observe and explain the pattern in the phenomenon according to which the gap in falling times decreases as the mass of falling objects increases.

2.5 Data analyses

2.5.1 The variable-oriented versus the person-oriented approaches

The analytical approaches used in this dissertation include both variable-oriented and person-oriented analysis (Bergman & Trost, 2006; Eye & Bogat, 2006). The underlying proposition in variable-oriented (or variable-centred) research is that populations are homogenous (Eye & Bogat, 2006), hence the focus is on identifying relations between variables or investigating mean differences. A variable-oriented approach was adopted in Studies I and II, the respective aims being to examine the relationships between instructional activities and epistemic emotions on the one hand, and science learning and epistemic emotions on the other.

The underlying proposition in person-oriented (or person-centred) research, in turn, is that populations are heterogenous, and that there may be distinct subgroups within them (Eye & Bogat, 2006). Thus, the focus is on individuals or distinctive groups, and the similarities or dissimilarities among them. This approach was adopted in Study III to investigate how students with different emotional trajectories made sense of a phenomenon. The variable-oriented and person-oriented approaches should not be perceived as being in opposition or in competition, instead, they rather represent complementary views of the same phenomena or constructs (Bergman & Trost, 2006).

2.5.2 Analyses of the qualitative data

Studies I and III relied on both qualitative and quantitative data. Video data, stimulated recall interviews and lesson plans provided by teachers were used in Study I to observe instructional activities in science lessons. First, the video excerpts were combined with the corresponding parts of the lesson plans and the interview transcripts. Second, a thematic analysis (Braun & Clarke, 2006) was conducted to systematically identify different instructional activities across the data set. The situations were organised according to their similar instructional activities. This was done based on the activities' purposes, activity formats and topics or assignments (Burns & Anderson, 1987). The following five categories of instructional activity were identified: (1) orienting and engaging activities, (2) conducting investigations, (3) analysing data and developing models, (4) teacher talk and (5) tasks for skills and content.

How students make sense of a phenomenon was evaluated in Study III based on their responses to the multiple-choice and open-ended POE items. Their individual response patterns were analysed and categorised by means of qualitative and inductive content analysis (Elo & Kyngäs, 2008). The focus in the data analysis was on the following issues: (1) whether the student observes that the gap in falling time was smaller in the last situation than in previous situations; and (2) whether the student was able to organise his or her observations into scientifically meaningful patterns, and thus to explain and make sense of the phenomenon. The students' response patterns were then categorised into three qualitatively distinctive main categories that illustrated their distinctive performance in scientific sensemaking. The categories were named *The inflexibles*, *The baffled ones* and *The elaborators*.

In both Studies I and III, the qualitative data was further examined in relation to quantitative data. This sets some requirements for the analysis of qualitative data. If qualitative data categories are to be used in statistical analyses the number of categories should be relatively small, and the number of cases in each category should be sufficiently large. Consequently, the subordinate activity categories first identified in the data in Study I were further collated into five representative main activity categories to facilitate the subsequent use of statistical analysis. The subsequent statistical analyses were also kept in mind when categorising the qualitative data in Study III. The final number of three main categories was considered optimal both for the statistical analyses and for illustrating the aspects of the data as well as possible. Furthermore, a researcher has to decide whether the categories of qualitative data should be considered nominal or ordinal. In Study I, the categories were clearly nominal, but in Study III, a closer consideration was required. Finally, it was concluded that a nominal approach would better represent the data, even if an ordinal approach would also have been defensible.

2.5.3 Statistical analyses

The Mplus statistical package, versions 8.2–8.5 (L. Muthén & Muthén, 2017) and the IBM SPSS Statistics package, version 26.0 were used for the statistical analyses. A repeated measures design was used in each of the studies to examine the students' epistemic emotions - measured up to 21 times using ESM in Studies I and II, and measured four times by means of a computer-based questionnaire in Study III. Having multiple measures of a single variable means that the situational observations are nested within the students. This hierarchical structure was taken into consideration in Studies I and II through the use of multilevel modelling: a multilevel regression analysis in Study I and a multilevel mediation analysis in Study II. In Study III, the first measure of epistemic emotions was used as a baseline measure, and the three subsequent measures served to construct longitudinal trajectories of emotions by means of latent class growth analysis (LCGA). In addition, correlational analyses were conducted in Study II, and non-parametric cross-tabulation analysis in Study III. The main statistical analyses are briefly described below.

Multilevel regression analysis

In multilevel modelling, it is acknowledged that responses within an individual may be more similar than responses between individuals. In other words, multilevel regression analysis allows the disentanglement of within- and between-level variability (Snijders & Bosker, 2012). In the hierarchical structure of ESM data, the repeated assessments (within-level) are nested within persons (between-level), which leads to a two-level model (Viechtbauer, 2022). Multilevel regression extends the standard regression by including so-called random effects (i.e., intercepts and/or slopes) in the model. As a result, the scores of the dependent variable for each situational (i.e., within-level) observation are predicted by the intercept that varies between individuals (i.e., between-level). In a random slope model, the independent variable is allowed to have a different effect (i.e., regression coefficient) for each individual.

A two-level regression analysis, with a random intercept and a fixed slope, was used in Study I to investigate the relationship between instructional activities and students' experiences of epistemic emotions. The activity categories were dummy coded and four different models, each with a different reference predictor, were used to examine the pairwise differences between the five instructional activities (the predictors).

Multilevel mediation analysis

In a mediation analysis, a simple regression analysis is extended by including multiple regressions in a single model. A mediation analysis is a special type of path analysis, in which the effect of independent variable (IV) on dependent variable (DV) is explained by a third, mediating, variable. A simple mediation analysis comprises three paths: the direct effect from the IV to the DV, the path from the IV to the mediator, and the path from the mediator to the DV. A multilevel modelling approach is needed if one or more of the variables in a mediation analysis is measured on the within level. Preacher and colleagues (2010) suggest a multilevel structural equation modelling (MSEM) framework, especially for models with a between-level outcome variable.

A two-level, parallel mediation analysis was conducted in Study II to estimate the direct and indirect (i.e., mediation) effects of prior knowledge and epistemic emotions on learning outcomes. A MSEM framework was applied (Preacher et al., 2010). In the case of parallel mediation, all the mediating variables, in this case epistemic emotions, are included in the same model. Because the predictor (prior knowledge) and the dependent variable (learning outcome) were measured on the between level, and only the mediators (epistemic emotions) were measured on the within level, all the interpretations were done on a between-level.

Latent class growth analysis (LCGA)

LCGA is a person-oriented analytical method that allows for the identification of distinctive longitudinal response patterns within a population (Jung & Wickrama, 2008; Nagin, 1999). It is a special type of growth mixture modelling (GMM; Muthén, 2004) in which the within-group variation is fixed at zero. In that fewer parameters are estimated in LCGA than in GMM, it is possible to run it with smaller datasets. Typically, several indicators of model fit are used to decide the number of latent classes because, as yet, no single indicator has been considered perfect (Nylund et al., 2007). Bayesian (BIC) and Akaike (AIC) information criteria are among the most frequently used fit indexes for model comparison (G. Schwarz, 1978). Low BIC and AIC values indicate a good model fit. In the Vuong–Lo–Mendell–Rubin test of fit (VLMR), the model fit of k classes is compared to k - 1 classes (Lo et al., 2001; Vuong, 1989). In other words, it is estimated whether an additional class significantly improves the fit. Thus, the best-fitting model is considered to have a significant (< .05) VLMR p-value. The entropy value of a model describes the quality of the classification (Celeux & Soromenho, 1996). It can range between 0 and 1, where 1 indicates perfect classification. In addition, decisions regarding the number of classes should be based on their theoretical consistency and interpretability.

LCGA was used in Study III to identify groups of students with distinctive longitudinal trajectories of epistemic emotions. A conditional analysis was applied, in which the baseline measures of epistemic emotions were used as covariates. The number of latent classes was decided based on five criteria: BIC, AIC, VLMR, the entropy criterion, and the clarity and interpretability of the classes.

2.6 Ethical considerations

The protocols of the three studies, as part of a larger research project, were approved by the University of Helsinki Ethics Review Board in Humanities and Social and Behavioral Sciences. In each case, participation in research activities was part of the regular schoolwork. Participation in the research itself was voluntary, and informed consent was required from all those whose data were used as part of the studied. The smartphones used in Studies I and II were for research purposes only and thus collected no personal data outside of the questionnaire. Three questionnaires per lesson were considered sufficient to capture versatile situations, while distracting from the teaching as little as possible. The data collection was planned to be pedagogical from the students' perspective, and conducted in alignment with the curriculum.

Table 1. Overview of Studies I, II and III: main aims, participants, variables, data collection methods and data analyses used in the original studies

	Study I	**Study II**	**Study III**
Main aim	To examine how different instructional activities relate to students' epistemic emotions in science classes	To examine the relationship between students' epistemic emotions and science learning	To examine the intertwinement between epistemic emotions and the development of scientific understanding
Participants	General upper secondary students (*N* = 100), from 5 classes	General upper secondary students (*N* = 148), from 6 classes	General upper secondary students (*N* = 113), from 6 classes
Variables	Epistemic emotions (surprise, curiosity, excitement, confusion, anxiety, frustration, boredom) Instructional activities	Epistemic emotions (surprise, curiosity, excitement, confusion, anxiety, frustration, boredom) Science learning	Epistemic emotions (surprise, curiosity, confusion, boredom) Scientific sensemaking
Data collection	Experience sampling Video observations Stimulated recall	Experience sampling Summative pre-posttest	Experience sampling Predict-Observe-Explain activity
Data analyses	Thematic analysis Two-level regression analysis	Correlational analyses Two-level parallel mediation analysis	Qualitative content analysis Latent class growth analysis Cross-tabulation

3 An overview of the original studies

3.1 Instructional activities predicting epistemic emotions in Finnish upper secondary school science lessons: Combining experience sampling and video observations (Study I)

The aim of Study I (Vilhunen et al., 2021) was to investigate how different instructional activities in science classes relate to experienced epistemic emotions. The research questions were:

- RQ1: What instructional activities can be found in PBL environments?
- RQ2: How do these instructional activities predict the levels of epistemic emotions that students experience and report during science lessons?

The data was collected during the implementation of a six-lesson project-based learning unit. The aim was to examine the situational epistemic emotions of the students, who responded to the ESM questionnaire based on beeps coming to their smartphones three times during each science lesson. This resulted in 1553 completed ESM questionnaires from 89 measurement situations. The instructional activities were studied through classroom video observations. The video data was supplemented with corresponding lesson plans and stimulated recall sessions with the teachers of the learning units. This qualitative data was analysed using thematic analysis, which revealed five categories of instructional activity: (1) orienting and engaging activities, (2) conducting investigations, (3) analysing data and developing models, (4) teacher talk and (5) tasks for skills and content. A two-level regression analysis was conducted to investigate how different instructional activities predicted the reported levels of epistemic emotions.

According to the results, orienting and engaging activities typically related to positive epistemic emotions such as excitement and curiosity. The students also reported the lowest levels of boredom during these activities. Activities that were cognitively more demanding, such as analysing data and developing models, and tasks for skills and content were associated with epistemic emotions that are more negative, such as confusion, anxiety and frustration. Conducting investigations was experienced as the least confusing activity. Furthermore, teacher talk induced the highest levels of boredom, and relatively low levels of surprise and confusion.

Overall, the findings show that the level of epistemic emotions varies significantly during science lessons with regard to different instructional activities. Thus, contextualising the subject matter and making it meaningful should be emphasised in science teaching so as to engage students in learning. The results also emphasize the importance of all phases of laboratory work: students should be active in asking scientific questions, planning investigations, as well as in collecting, analysing and interpreting data.

3.2 Clarifying the relation between epistemic emotions and learning by using experience sampling method and pre-posttest design (Study II)

The aim of Study II (Vilhunen, Turkkila, et al., 2022) was to clarify the hypothesised relationship between epistemic emotions and learning. Situational measures of emotions were used to examine both the correlational relations and the causal effects, and student learning was assessed by means of summative pre-and post-testing. The research question was:

- RQ1: How do epistemic emotions relate to students' performance and learning in the context of upper secondary school science?

The participants of the study were physics students in the first year of upper secondary school. The data were collected during a study period comprising six or seven consecutive lessons focusing on Newtonian mechanics. Students' previous knowledge and learning outcomes were evaluated by means of pretesting and posttesting. The same test served as both a pretest and a posttest, and it included topics covered within the study period. ESM was used to gather data on the students' experiences of situational epistemic emotions: they filled out an ESM questionnaire in response to beeps coming to their smartphones on three occasions during each science lesson (n = 1801 ESM observations). The correlational relationship between epistemic emotions and test performance was examined by means of bivariate Pearson correlations, using the aggregated mean values of epistemic emotions. To examine the causal relations between prior knowledge, situational epistemic emotions and learning outcome, a mediation analysis with MSEM approach was conducted. Using MSEM, the effect of epistemic emotions on the change in performance was estimated, or in other words, the learning progress taking place during the study period.

According to the MSEM results, prior knowledge (pretest performance) was the strongest predictor of learning outcomes (posttest performance). When this was taken into account, boredom was the only epistemic emotion that had a significant effect on the outcome: in other words, it was the only emotion that seemed to affect students' learning during the period. The correlational analyses also showed that epistemic emotions related to both pretest and posttest performance; that curiosity and excitement correlated positively with performance; and that frustration and boredom correlated negatively with performance.

Taken together, the findings clearly indicate the relevance of emotions in learning contexts. However, the relationship between emotions and learning seemed to be very different depending on whether correlational or causal models were used. The findings underline the complexity of the interplay between emotions and learning, and raise questions about the state versus trait nature of epistemic emotions.

3.3 Epistemic emotions and observations are intertwined in scientific sensemaking: A study among upper secondary physics students (Study III)

The aim of Study III (Vilhunen, Chiu, et al., 2022) was to investigate the entangled relationship between situational epistemic emotions and the development of students' scientific understanding. The research questions were:

- RQ1: How do students perform in making sense of the motion phenomenon within a three-cycle POE activity?
- RQ2: What kind of trajectories of situational epistemic emotions can be identified among students when making sense of the phenomenon within the POE activity?
- RQ3: How is student performance in scientific sensemaking related to their trajectories of situational epistemic emotions?

The participants were first-year students of physics in upper secondary school. The data were collected during a computer-based POE activity in which students were introduced to three different situations concerning fall motion. The students' performance in scientific sensemaking was evaluated from their responses to POE items and categorised through qualitative content analysis. Situational epistemic emotions were measured on a four-point Likert scale after each of the three POE cycles. LCGA was used to identify groups of students with distinctive emotional trajectories. Finally, the relationship between performance in POE activity and emotional trajectories was explored by means of cross-tabulation (chi-square test).

Based on the qualitative content analysis, three distinctive categories were identified: first, *The inflexibles* did not make the correct observations in the POE activity and thus were unable to make sense of the phenomenon; second, *The baffled ones* were able to make the correct observation in the last POE cycle but were not able properly to make sense of the phenomenon; and third, *The elaborators* were able to make the correct observation and to explain the correct pattern in the phenomenon explicitly. The LCGA revealed two latent classes illustrating different emotional trajectories: the first was characterized by high levels of curiosity and increasing levels of surprise and confusion, and the second by constantly high levels of boredom. According to the results of the chi-square test, students' inability to make relevant observations related significantly to experienced boredom, and those who were better able to make sense of the phenomenon were more likely to experience surprise, curiosity and confusion.

In sum, the results imply a need in science education to engage students in curiously observing and testing predictions. Furthermore, the findings underline the importance of epistemic emotions in educational settings, and the entanglement of cognitive and affective factors in learning situations.

4 Discussion

The focus in this chapter is on the main findings from Studies I, II and III. First, the empirical, theoretical, methodological and practical contributions are considered. The empirical aims of the thesis were to explore how instructional activities as contextual factors in science lessons relate to students' experiences of epistemic emotions, and how their epistemic emotions relate to their science learning. On the theoretical level the aim was to enhance understanding of the role that epistemic emotions play in authentic contexts of science learning, and thereby to contribute to the discussion on students' academic emotions. The main methodological aims were to apply advanced and versatile statistical methods in examining situational emotions, and to combine qualitative with quantitative data to better contextualise students' situational experiences in authentic science learning environments. The practical aim was to provide new insights and recommendations for teachers and other practitioners in the field of science education whereby they could give students more support in their science learning. The limitations of the research are discussed at the end of the chapter.

4.1 Empirical findings

4.1.1 Instructional activities related to students' experiences of situational epistemic emotions

The question concerning students' experiences of epistemic emotions in different instructional activities was addressed in Study I in particular, but it was also touched upon in Study III. According to the multilevel regression analysis reported in Study I, the level of epistemic emotions varies significantly during science lessons with regard to different instructional activities.

First, orienting and engaging activities, as conceptualised in Study I, appear to be particularly relevant in terms of inducing positive epistemic emotions such as excitement and curiosity, and preventing boredom. According to another study, these activities are also related to aroused interest in students (Vilhunen, Lavonen, et al., 2022). Also, previous research has shown that introductory or demonstration activities can arouse positive emotions in students (King et al., 2015).

In a way, the computer-based learning activity described in Study III could also be considered an engaging and orienting activity: it was implemented as an introductory exercise in the study period, the aim being to engage students in actively observing and coming up with scientific questions. In this regard, the findings from Study III corroborate those from Study I: the majority of the students belonged to the latent class characterised by high levels of curiosity in addition to increasing levels of surprise and confusion.

The above findings can be considered expected. Excitement and curiosity are likely to occur when the aim of the teacher is to orient students towards and engage them in learning. Previous studies have also reported a positive relation between curiosity and engagement (Bosch & D'Mello, 2017), as well as curiosity and knowledge-exploration behaviour (Gruber & Ranganath, 2019; Liquin & Lombrozo, 2020; Vogl et al., 2020).

Second, cognitive load and taking an active role in learning seem to affect students' epistemic emotions. The instructional activities categorised in Study I as "Conducting investigations and analysing data" and "Developing models" could be considered scientific practices, as described in previous literature (Krajcik & Shin, 2014; National Research Council, 2012). Together, they could even be classified as "doing laboratory work". However, in terms of the epistemic emotions they induce, they differ significantly. The cognitively less demanding practical part of laboratory work (conducting investigations) induces relatively low levels of anxiety, confusion and frustration, whereas the computational and conceptual aspects (analysing data and developing models) with a higher cognitive load induce significantly more anxiety, confusion and frustration among students.

The role of cognitive load on students' epistemic emotions seems plausible also based on the results of Study III. The cognitive load of the POE task increases towards the end of the activity as many students experience the information in the last situation as incongruent. Simultaneously, the experienced levels of surprise and confusion among the students seemed to increase. These findings are in line with previous research results indicating an interrelation between cognitive load and negative, activating emotions (Cheng et al., 2020; M. Han & Gutierez, 2021; Hong et al., 2017) in the context of science education.

Taking an active role in a learning activity could also increase students' cognitive load. Thus, a similar difference as between the practical and computational parts of laboratory work is evident among the more traditional categories of instructional activity used in Study I, namely "Teacher talk" and "Tasks for skills and content". The most prevalent epistemic emotion students experience during teacher talk is boredom, which is in line with findings reported in previous research (Mann & Robinson, 2009). By contrast, when students work with tasks for skills and content, they experience relatively high levels of anxiety, confusion, and frustration. These activities may both include different levels of cognitive demand, from low to high. However, a student's role in these activities differs significantly. Students may choose to play a passive role during teacher talk, even when it is interactive, and thus eventually become bored. Tasks, on the other hand, require students to be active learners, which again may increase the cognitive load and further induce negatively valenced epistemic emotions.

Thus, analysing data and developing models, in addition to working on tasks focused on skills and content, can be seen as the most demanding classroom activities from the students' perspective: they relate to higher levels of confusion, frustration and anxiety than some of the other instructional activities. Indeed, it was also found in another study that activities requiring computational thinking and active participation are among the most challenging for students (Vilhunen, Lavonen, et al., 2022).

The effect of student activity on their epistemic emotions is also visible in the results of Study III. Almost half of the students in the data were notably bored throughout the learning task, and many also gave relatively short and vague answers in the POE items. This implies that these students were not actively engaged in the learning activity, but were only passively executing the given task. It has also been suggested in previous research that passive participation in learning activities induces boredom (Minkley et al., 2017). Thus, it could be argued that high cognitive demand and the student's active role induce negative, activating epistemic emotions. In turn, low cognitive demand and a passive role may induce boredom.

4.1.2 Associations between students' epistemic emotions and science learning

Studies II and III addressed the question concerning the relationship between students' epistemic emotions and science learning. A pre-posttest design was adopted in Study II to examine science learning, and in Study III, science learning was conceptualised through scientific sensemaking and examined within the POE activity.

In Study II, as hypothesized, positive epistemic emotions (curiosity and excitement) were found to correlate positively with pretest and posttest performance, and negative epistemic emotions (frustration and boredom) to correlate negatively with pretest and posttest performance. This finding is consistent with results reported in previous literature (Ainley & Ainley, 2011; Bosch & D'Mello, 2017; Gruber et al., 2014; Muis et al., 2015; Pekrun et al., 2014), and thus further confirms the association between epistemic emotions and performance. However, surprise was not found to relate to performance, even though the results of some previous, experimental studies imply an existing relation between surprise and learning (Chiu et al., 2014; Muis et al., 2018). Furthermore, there was no significant correlation between test performance and the negatively valenced emotions of confusion and anxiety. However, these emotions may play an interesting role in learning. They had a relatively strong positive correlation with frustration and boredom that relate negatively to performance, but at the same time a clear positive correlation with curiosity that relates positively with learning. Thus, this may indicate that these emotions occur simultaneously in situations, where curiosity is triggered by new knowledge, but high cognitive demands also cause confusion and anxiety.

Despite the clear correlational relations between epistemic emotions and test performance, the MSEM approach also employed in Study II did not indicate such a strong relationship between situational emotions and learning. Based on MSEM, only boredom had an effect on learning outcome after controlling for prior knowledge. In other words, the more bored students are when studying, the less likely they are to learn. These results are in line with and complement previous findings of a negative relationship between boredom and learning (Pekrun et al., 2014; Tze et al., 2016).

Interestingly, even though curiosity, excitement and frustration correlated strongly with both pretest and posttest performance, they did not relate to change in performance during the study period. However, also the correlation with performance could be assumed to indicate something about how they relate to learning. Students with high situational experiences of curiosity and excitement and low experiences of frustration performed better not only in the pretest but also, due to strong autoregression, in the posttest. In other words, at some point these students have either learned more due to a tendency to experience high curiosity and excitement and low frustration, or they have developed a tendency to have these emotional experiences due to their previous performance.

The results of Study III are in line with those of Study II, indicating that levels of epistemic emotions vary significantly especially in relation to students' ability to make relevant observations. As revealed in a cross-tabulation, students whose emotional trajectories indicate high levels of curiosity and increasing levels of surprise and confusion are better able to make sense of the phenomenon than students with high levels of boredom. This implies that boredom may have an inhibiting effect on making observations and developing understanding, as has been suggested in previous research (Muis et al., 2015; Pekrun et al., 2014; Tze et al., 2016). Correspondingly, curiosity, confusion and surprise may foster these cognitive processes. As Muis and colleagues (2015) suggest, different learning strategies related to these emotions may explain this implication. Activating epistemic emotions such as surprise, curiosity and confusion typically relate to deep-processing learning strategies. Moreover, curiosity in particular plays a role in critical thinking, related to the application of previous knowledge to new situations and the evaluation of information (Muis et al., 2015). These deep-processing learning strategies also play a central role in the making of scientific observations. In turn, as a negative deactivating emotion, boredom is related to the impairment of any learning strategies, which in the case of Study III appears as the inability or unwillingness to make scientifically relevant observations. Overall, the findings corroborate the assumption that emotions influence scientific sensemaking and reasoning (Fischer et al., 2014; Theobald & Brod, 2021; Wickman et al., 2021).

Overall, the role of confusion in learning is noteworthy. Even if it is a negative emotion based on its valence, in terms of learning it could be considered positive. It was found in Study II that confusion did not relate significantly to performance or learning, but it correlated positively with curiosity. Furthermore, the regression coefficient from pretest performance to situational confusion in MSEM was negative (and statistically significant), but the regression coefficient from situational confusion to posttest performance was positive (but statistically non-significant, $p = 0.07$), underlining the complexity of the interplay between learning and situational confusion (D'Mello et al., 2014). As indicated in the findings from Study III, confusion often appears together with the positive emotions of curiosity and surprise, and is thus experienced by students who perform better in scientific sensemaking. These findings are in line with the results of previous research suggesting a positive relationship between confusion and learning (D'Mello et al., 2014; Muis et al., 2015; Watkins et al., 2018), but contradict other research findings indicating that confusion detracts from learning (Jacobson et al., 2021; Schneider et al., 2016). Indeed, the present results indicate that situational confusion should also be considered a learning enhancer rather than only a detractor. However, further research should be carried out to establish the role of confusion in science learning.

4.2 Theoretical considerations

4.2.1 The trait versus state nature of epistemic emotions

As the results of Study II show, even though the relationship between emotions and performance seems clear, this is not the case regarding emotions and *change* in performance (i.e., learning). This leads to the issue of the trait versus state nature of epistemic emotions. As described in the introductory chapter of this thesis, emotions are typically defined as affective states (Ekman, 1992; Russell, 2003; Shuman & Scherer, 2014). However, some individuals may have a trait-like disposition to experiencing certain types of emotional states (Graham & Taylor, 2014). Indeed, this trait-type disposition presumably has an effect on students' performance and situational emotions. On the other hand, state-type situational emotions may plausibly develop into trait-type dispositions through performance-related feedback and appraisal. According to previous literature, also interest may develop from state-type situational interest to trait-like individual interest (Hidi & Renninger, 2006). Thus, hypothetically this could happen also with other affective factors, such as epistemic emotions in this case. However, trait-like emotions by definition come close to attitudes and should then not be referred to as emotions at all (Shuman & Scherer, 2014). On the other hand, attitudes may also play an important role in learning (Cahill et al., 2018), and therefore should not be ignored.

All in all, the trait versus state nature of emotions should be taken into account in future research focusing on emotions as situational constructs. It is advisable to measure emotions in particular situations of interest, otherwise, if measured retrospectively, they may reflect students' moods or attitudes more than the situational experiences per se. Furthermore, background questionnaires on attitudes or moods could yield valuable information about how students are disposed to experiencing certain emotions.

4.2.2 Activating versus deactivating emotions

One could conclude from the results of the three studies that the negative deactivating emotion of boredom is the only epistemic emotion that undisputedly plays a negative role in learning. The beneficial role of positive activating emotions has been demonstrated already in previous studies (e.g., Camacho-Morles et al., 2021; Obergriesser & Stoeger, 2020; Pekrun et al., 2018), and is further confirmed in the present research. However, and especially in the context of science education, also the role of negative activating emotions seems plausibly beneficial in terms of learning. As shown in Studies II and III, negative activating emotions tend to correlate or to occur with curiosity. This finding reflects the suggestion by Pekrun et al. (2017, p. 1272) that "emotions during epistemic activities are primarily linked along the arousal dimension of emotion rather than the valence dimension". Furthermore, as suggested in Study I, negative activating emotions tend to occur in situations of high cognitive demand, such as developing models. Such activities are pertinent to science, however, and could be considered to advance scientific understanding and hence learning. Thus, it could be concluded that the negative deactivating emotion of boredom is detrimental to learning, but that activating emotions are beneficial, or at least pertinent, regardless of their valence.

On the other hand, it can be questioned, if boredom is even an emotion (Eliot & Hirumi, 2019). If emotions are defined as affective episodes caused by a stimulus or an antecedent, with an object (Ekman, 1992; Russell, 2003; Shuman & Scherer, 2014), it raises the question of the eminently lacking stimulus or object of boredom. Moreover, if emotions are considered, from a biological perspective, to be adaptations that prepare individuals to react in an appropriate way to environmental factors (Cosmides & Tooby, 2000), the question arises as to whether boredom really prepares an individual to *react*. It could rather be defined as a "lack of emotion", as not having stimulus or object, and as an affective state in which there is no need to react to environmental factors. Thus, it could be concluded that, with regard to learning, emotional arousal, or the readiness to react to external stimuli, is beneficial, regardless of the valence.

4.3 Methodological contributions

Both variable-oriented and person-oriented approaches, as well as qualitative and quantitative methods were used in this research to investigate the relations linking epistemic emotions, instructional activities and science learning. Variable-oriented approaches have dominated previous research (e.g., Brod & Breitwieser, 2019; Dávila-Acedo et al., 2021; Jacobson et al., 2021; Theobald & Brod, 2021), and only a limited number of studies have taken a person-oriented approach (e.g., Cheng et al., 2020). Variable-centred studies have value in providing information about individuals *on average*, whereas person-oriented research addresses differences *between* individuals. Thus, using person-oriented approaches, in addition to variable-oriented approaches, to investigate students' emotions in science education contexts could shed new light on the phenomenon.

In the three sub-studies comprising this thesis, qualitative data was examined in relation to quantitative data on epistemic emotion. This requires a substantial grouping of qualitative data and a reduction in the number of categories to meet the requirements of statistical analysis. However, the use of versatile data sources and data sets may increase the credibility of the study. Furthermore, in Study I, multiple qualitative data sources (i.e., video recordings, lesson plans, and stimulated recall interviews) were used to gather as holistic view as possible of instructional activities in science lessons. Activities in classrooms are commonly observed by means of self-reports (Inkinen et al., 2019), video observations (Schmidt et al., 2018) or field notes (Christensen et al., 2015; Turkkila et al., 2021), for example. However, it could be concluded from the experiences of Study I that multiple data sources may provide a more accurate view of a phenomenon. In particular, when the focus of interest is on instructional activities, in other words teachers' plans and intentions, relying only on video observations or field notes may leave much to the researcher's speculation or interpretation. Self-reports, on the other hand, give valuable information on students' *experiences* of the activities, but could be far from the teacher's intended activities. Thus, combining multiple data sources (i.e., triangulation; Noble & Heale, 2019) could increase the validity of a study.

Furthermore, mixing different data collection approaches with ESM could bring out new perspectives and enable the validation of ESM data beyond the detection of instructional activities. Combining ESM with observational scoring systems (e.g., CLASS-S by Pianta et al., 2012) to examine teacher-student interaction, for example, or with eye-tracking (e.g., Miller, 2015) to study student engagement, would give a broader understanding of the contexts in which students' epistemic emotions emerge, thus providing new and interesting insights into the educational research taking place in authentic classroom environments.

In Studies I and II, ESM was used in a relatively traditional way (Dejonckheere & Erbas, 2022): students filled in a smartphone-delivered questionnaire multiple times per lesson, and during several consecutive lessons. However, in Study III, the guidelines for conducting ESM research were utilised to conduct a questionnaire in a computer-based learning environment, during a single well-defined learning activity. There has been a remarkable increase in the use of digital tools and computers in education in recent years, including online teaching and learning. This opens up new possibilities for ESM studies. For example, integrating ESM questionnaires into a digital learning environment could notably simplify data collection procedures.

4.4 Practical implications

Given the results reported in this dissertation and in previous literature, the beneficial role of positive emotions in learning seems evident (e.g., Pekrun et al., 2018). Teachers therefore play an important role in fostering these positive emotions in everyday schoolwork. As demonstrated in Study I, teachers could try to promote positive emotions and to stifle boredom by employing certain instructional activities, such as demonstrations and other orienting activities. Engaging students in learning by contextualising the subject matter and making it meaningful should be emphasised in teaching. Furthermore, future studies should focus on identifying the specific factors in these engaging activities that make students excited and curious, and on determining whether the same factors could be incorporated into other activities. Moreover, as shown in previous research, teacher support has an effect on students' emotions (Lei et al., 2018).

As also discussed in previous chapters, negatively valenced emotions are pertinent to science learning. Students in science education are sometimes scaffolded in open inquiry activities to actively construct knowledge by themselves, instead of just giving the right answers. The presence of negative emotions seems natural in such situations, even fundamental (DeBellis & Goldin, 2006; Radoff et al., 2019). Thus, on the basis of previous research and the results of the three studies discussed above, I argue that students need not only cognitive, but also *emotional scaffolding* when learning science. Teacher support and emotional scaffolding are particularly pertinent in situations that induce anxiety, confusion, or frustration.

Teachers could also support students in transforming negative affective experiences into positive meta-affects (DeBellis & Goldin, 2006; Reeve & Halusic, 2009). For example, teachers could verbally point out that challenging tasks are primarily learning opportunities and opportunities to receive feedback. Teachers could explain that a certain activity will be challenging and thus could arouse some negative emotions, but that such emotions are meaningful in terms of learning and developing one's understanding. In the context of science education, teachers could also highlight the process-like nature of learning and the role of issues that have already been learnt. Thus, students could learn to believe that negative emotions related to difficult tasks eventually lead to new realisations and new understandings. In conclusion, to promote the development of positive meta-affects, the instruction should be planned so that, as a whole, the learning process is positive for students. Positive learning experiences should include enough challenges and even confusion, but eventually also provide students with a positive experience of realising and succeeding. Thus, to support the development of positive meta-affects, teaching and learning should occur in students' proximal zone of development (Vygotski, 1978).

Finally, it is obvious that not all students experience activities in the same way. Thus, it is worthwhile for teachers to observe students' emotional states, so that they could direct the support and scaffolding to those who seem to be frustrated or bored, for example. On the other hand, observing students' emotional states may be difficult, since the underlying feelings are not necessarily evident on the outside (Loukomies et al., 2015). All in all, this underlines the importance of teacher expertise in, first, recognising and, second, scaffolding students who need support, whether it be emotional or cognitive. Emotional aspects of learning should therefore be considered already in teacher training.

4.5 Limitations

By definition, epistemic emotions have an object focus on knowledge or knowledge construction. In this research, the epistemic emotions identified in earlier studies were investigated (Pekrun et al., 2017). However, the questionnaires used in this research only required students to indicate the extent to which they felt surprised, curious, excited, confused, anxious, frustrated or bored, and not what the object of their emotion was. Thus, the emotions under study were not necessarily epistemic in nature. For example, emotions such as excitement and anxiety may have an object focus on something other than the knowledge processed in a given situation (e.g., in the topic or achievement). However, other emotions such as confusion and curiosity could be regarded as more epistemic in nature, in other words more likely to have an object focus on knowledge itself.

The ESM data used in this study was collected three times, at random points, during each science lesson of the study period. The researchers and teachers together concluded that this was the maximum number of beeps per lesson so as not to disturb the instruction more than was necessary, but at the same time to cover a versatile set of situations. However, emotions typically occur in episodes of varying length (Verduyn et al., 2009), which most probably means that not all the emotional episodes are captured in the ESM data. This is supposedly the case with surprise in particular, which typically occurs in relatively short episodes (Horstmann, 2006; Noordewier et al., 2016). Surprise appeared as a relatively non-significant variable in Studies I and II, which in light of previous research is not normally the case (Chiu et al., 2014; Theobald & Brod, 2021). It is also possible that some emotions that are typically longer lasting persisted from one situation to another, thus reflecting a situational stimulus other than the one observed at the time of the ESM measures. To capture more detailed data on emotions, the data collection should be more intensive (e.g., focusing on facial expressions instead of self-report questionnaires) or on predetermined points of the instruction, as in Study III. Longitudinal analyses of such intensive data would also enable a more detailed examination of emotional trajectories.

Mood or other personal dispositions to experiencing certain types of emotion could influence situational emotions (Shuman & Scherer, 2014). Acquired knowledge and preconceptions also influence students' affective experiences during learning (Gupta et al., 2018; Liu et al., 2014; Putwain et al., 2018). However, a comprehensive background questionnaire was not part of this research. Taking into account affective and cognitive background variables in future studies would make it possible to explore in more detail what really takes place in the situation, and what students bring to learning situations, both affectively and cognitively.

Collecting situational data in authentic environments instead of highly controlled laboratory settings also has its limitations. For example, there are always several factors influencing the variables of interest that cannot be controlled, or even identified. In classroom contexts, such factors include for example social relationships, the physical conditions in the learning environment, and the time of day, week, or semester. Tensions such as these between the advantages and disadvantages of laboratory and authentic contexts will always remain, and thus should be acknowledged in all educational research.

Missing data may decrease the validity of the research. The data used in the three studies comprising this thesis were only qualitatively screened in terms of missing data, and were deemed acceptable. Thus, not all issues related to missing data were considered in detail. First, some students in each of the participating classes chose not to take part in the research. It is probable that some personal characteristics affected their willingness to participate, thus the sample does not represent the population (i.e., the participating schools or classes) in an optimal way. For example, females were slightly overrepresented in the sample used in Study II (Official Statistics in Finland, 2020). Second, some missing data in ESM studies is typically attributable to participant drop-out (Dejonckheere & Erbas, 2022), meaning that some participants do not reach the end of the study. Again, it is likely that some participant characteristics or experiences during the study led to the drop-out. Third, some ESM responses were also missing in between the data collection period. For example, the students participating in Studies I and II were told that it was acceptable not to fill in the questionnaire if it disturbed their current activities too much. Thus, it is possible that some chose to ignore the ESM notifications in the most engaging situations. On the other hand, extreme boredom could also be assumed to cause people to miss notifications. Overall, it is very likely that the missing data was not completely random, thus decreasing the validity of the study.

Self-report questionnaires in general have their limitations, such as social desirability bias and misinterpretation by participants (Duckworth & Yeager, 2015). Social desirability bias means that students may fake their answers to make them appear socially desirable or acceptable, even if the data collection is anonymous. Students in the current research with a high personal interest in and appreciation of science, for example, may tend to give relatively high scores to positive emotions in all situations. This again highlights the value of background questionnaires in ESM studies. Misinterpretation means that a student may read or interpret an item in a way that is not intended by the researcher. The items used for measuring emotions in this research were supposedly relatively well understood by the students. However, translating emotions is not always easy, which may cause difficulties in comparing findings based on questionnaires conducted in different languages. As an example, the words “curious” and “confused” have a slightly different tone when translated into Finnish: the Finnish word for “curious”, namely “utelias”, has a slightly more negative connotation because in addition to meaning “curious” it can also connote “nosy”. However, in the school context, students probably interpret the word “utelias” as intended. Further, the Finnish word for “confused”, namely “hämmentynyt”, also has a slightly more negative connotation and would translate equally well as “baffled” or “bewildered”. Thus, students would not necessarily report being very confused if at the same time they felt curious or interested and were engaged in learning. A short version of EES (Pekrun et al., 2017) was used in this research. Single-item instruments such as this are even more vulnerable to misinterpretation and translation issues than a multiple-item scale would be. However, the use of single-item scale is justified in an ESM study to reduce the burden on participants.

Finally, the generalisability of results is also subject to certain limitations. First, all the data was gathered during physics courses in an upper secondary school, in the context of studying Newtonian mechanics, and in one geographically limited area in Southern Finland. A more versatile data collection including different subjects and participants from different backgrounds, for example, would give more generalisable results. Second, the sample sizes in the three studies were relatively small, thus leaving open the possibility that repeating them might lead to slightly different results.

5 Conclusion

The research presented in this thesis enhances current understanding of the role of situational epistemic emotions in science education. The specific aims were to explore how instructional activities in science lessons relate to students' emotions, and to examine the association between the emotions and science learning. This research, covering all phases of the teaching-studying-learning process, provides novel perspectives for science educators and researchers on how students' emotions and development of scientific understanding are intertwined in authentic contexts of science learning.

First, the findings revealed that students' emotional experiences in science lessons can be managed through instructional activities. Orienting and engaging activities most typically relate to positive epistemic emotions, whereas cognitively demanding activities tend to arouse more negative emotions. This knowledge could provide both researchers and practitioners with the tools to promote beneficial and discourage adverse epistemic emotions in educational settings, thus helping teachers to design emotion-aware learning environments and support students through emotional scaffolding. Second, there were significant and meaningful associations between epistemic emotions and science learning. Although the findings corroborated the positive relationship between positive emotions and learning, the thesis also highlighted the plausibly beneficial role of negative activating emotions in science learning. These results in combination imply that engaging students in curiously making sense of scientific concepts and phenomena should be an important mission for educators and other practitioners.

Overall, the findings underline the importance of epistemic emotions in educational settings, and the complexity of the interplay between cognitive and affective factors in learning situations. Thus, the role of students' situational emotions should be acknowledged in future research, as well as in school settings, teacher training and educational policymaking.

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The original publications are not included in the electronic version of the dissertation.