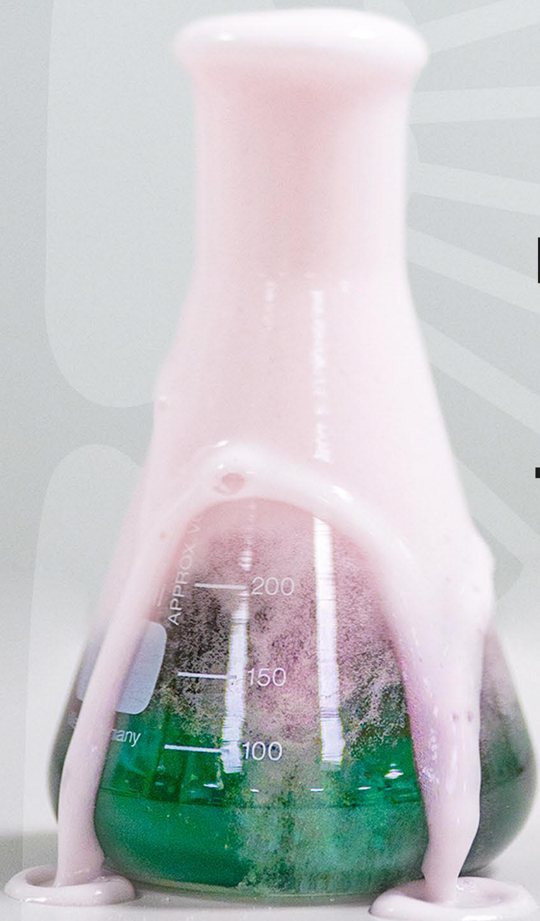
TURUN YLIOPISTO
UNIVERSITY OF TURKU

Moments of Mistakes

Students’ Affective Responses in an Undergraduate Chemistry Laboratory Course

Reetta Kyynäräinen



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I dedicate this work to all the invaluable mistakes that led to this thesis.

"On the other hand, wasn't that the very definition of life?
Constant adaptation brought about by a series of never-ending mistakes?"
– Bonnie Garmus, Lessons in Chemistry

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ABSTRACT

Mistakes are often associated with negative connotations. However, they are an intrinsic part of learning science, particularly in inquiry-based settings, and students should therefore feel comfortable encountering them. Yet, research focusing on students' abilities and dispositions in navigating mistake situations remains scarce; thus, the purpose of this thesis is to provide insights into students' affective responses to mistakes across achievement situations in an undergraduate chemistry laboratory course. It is hypothesized that students' affective reactions may be influenced by individual, situational, and contextual factors, which are examined in the thesis.

The thesis comprises three original studies: Study I investigated how mistakes in the chemistry laboratory shape students' situational engagement, Study II focused on students' emotional responses to laboratory mistakes, and Study III examined how mistakes in pre-lab activities influenced their situational engagement and how those predicted situational engagement in the subsequent laboratory sessions. All sub-studies employed an ecological momentary assessment design, collecting students' momentary experiences in ecologically valid contexts, including the teaching laboratory and the online learning environment, for pre-lab activities. The data were analyzed within the multilevel structural equation modeling framework.

Four main findings emerged: 1) mistakes occur frequently and are an inseparable part of the learning experience, 2) there is great variability in students' affective responses based on individual, situational, and contextual factors, 3) in general, mistakes trigger relatively negative affective responses (i.e., lower levels of positive emotions and perceived skills, and higher levels of negative activating emotions and perceived challenge), and, due to the increased challenge and emotional activation, they may also have a motivating effect, and 4) in terms of the affect, students might overcome their mistakes in a relatively short time. Moreover, the findings contribute to the discourse of chemistry laboratory education reform, framing the navigation of mistake situations as a central learning objective. The research underpins the need for affective support, particularly for targeted groups of students, such as low-performers and those with high emotional costs, especially in the face of mistakes that are conceptual and caused by the lack of their own expertise.

KEYWORDS: affective learning, mistakes, ecological momentary assessment, laboratory education, chemistry education

TURUN YLIOPISTO
Matemaattis-luonnontieteellinen tiedekunta
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TIIVISTELMÄ

Virheisiin liittyy usein negatiivisia mielleyhtymiä. Ne ovat kuitenkin keskeinen osa luonnontieteiden oppimista – erityisesti tutkimuksellisuutta – ja näin ollen opiskelijoiden olisi tärkeää olla sinut virheiden kohtaamisen kanssa. Ymmärrys opiskelijoiden taidoista ja taipumuksista käsitellä virheitä on kuitenkin yhä hyvin vajaata, ja tämä tutkimus vastaa tutkimusaukkoon tuottamalla tietoa yliopisto-opiskelijoiden affektiivisista reaktioista kemian harjoitustyökurssilla. Oletuksena on, että virhereaktioiden laatuun vaikuttavat yksilölliset, tilannekohtaiset ja kontekstuaaliset tekijät, ja näiden vaikutuksia tarkastellaan tässä väitöskirjatutkimuksessa.

Väitöskirja koostuu kolmesta osatutkimuksesta: Tutkimus I tarkastelee miten virheet vaikuttavat opiskelijoiden tilannekohtaiseen sitoutumiseen laboratorio-ympäristössä, Tutkimus II keskittyy opiskelijoiden tunnereaktioihin laboratoriossa ja Tutkimus III käsittelee ennakkotehtävien aikaisten virheiden vaikutusta opiskelijoiden tilannekohtaiseen sitoutumiseen sekä siihen, miten ne ennustavat sitoutumista seuraavan laboratoriotyön aikana. Kaikissa osatutkimuksissa hyödynnettiin kokemusotantamenetelmää, joka tuottaa tietoa opiskelijoiden hetkellisistä kokemuksista ekologisesti valideissa konteksteissa: kemian opetuslaboratoriossa sekä sähköisessä oppimisympäristössä, jossa ennakkotehtävät tuli suorittaa. Aineisto analysoitiin hyödyntämällä monitasoista rakenneyhtälömallinnusta sekä sen sovelluksia.

Tutkimuksesta saatiin neljä päätulosta: 1) virheitä tapahtuu jatkuvasti ja ne ovat erottamaton osa oppimiskokemusta, 2) opiskelijoiden affektiiviset reaktiot riippuvat voimakkaasti yksilöllisistä, tilannekohtaisista sekä kontekstuaalisista tekijöistä, 3) keskimäärin, virheet aiheuttavat suhteellisen negatiivisen affektiivisen vasteen: osaamisenkokemus sekä positiiviset tunteet vähe-nevät ja koetut haasteet sekä negatiiviset aktivoivat tunteet voimistuvat; toisaalta haastavuudenkokemus ja korkeampi aktivaatio voivat viitata virheiden mahdolliseen motivoivaan vaikutukseen, ja 4) opiskelijoiden tunnereaktiot virheisiin eivät ole kovin pitkäkestoisia. Lisäksi tulokset tukevat virheiden käsittelyn nimeämistä kemian laboratorio-opetuksen oppimistavoitteeksi ja korostavat affektiivisen tuen tarvetta, erityisesti opiskelijoille, jotka suoriutuvat heikommin tai kokevat korkeita emotionaalisia kustannuksia, erityisesti jos virhe on konseptuaalinen tai johtuu opiskelijan osaamisen puutteesta.

ASIASANAT: affektiivinen oppiminen, virheet, kokemusotantamenetelmä, laboratorio-opetus, kemian opetus

Acknowledgements

Oh my. I had imagined that this would be an emotional endeavour, but little did I know that as soon as I began writing this section, my eyes would immediately fill with tears of joy and gratitude. In the background, a gentle melody plays – I always write with music – and fittingly, the piece is titled *Finding Your Way Home*. The name feels like the perfect reflection of this journey. I have, in so many ways, found my way home, to belonging, and for that, I am indebted to so many beautiful people who have accompanied me along the way.

First and foremost, I owe my deepest and sincerest thanks to my main supervisor, Veli-Matti Vesterinen. My gratitude to you goes beyond words, let alone these few lines – if it wasn't for you, any of this would not have happened. Thank you for encouraging me to embark on this journey, for seeing the spark in me and feeding it until my love for research burst into flames. I have been privileged to work with such a humane, excited, humorous, and wise supervisor, mentor, and person. In addition, I would like to express my gratitude to my two other brilliant supervisors. Thank you, Mikko-Jussi Laakso, for your unwavering faith in my abilities; knowing that you believe in me has encouraged me to strive for excellence. You're one of the most visionary, motivational, and empowering people that I've ever met. Finally, Elisa Vilhunen, thank you for bringing your expertise, enthusiasm, precision, and your candid, forthright support into the supervisory team. I can relate to you in many ways, and I've felt like I could always count on you, for which I am so thankful.

Second, I would like to extend my sincere thanks to the two external reviewers, Professor Ann Renninger and Professor Sebastian Habig, for their time, effort, and careful reading of the dissertation. I truly appreciate their expert comments that helped me refine the text to its final form. I am also grateful to Professor Joseph Krajcik for accepting the invitation to act as an opponent at the public defence of my dissertation – what an honor. Further, I would like to thank the funders of this study, the Research Council of Finland and the Ministry of Education and Culture. It has been a privilege to get to focus on working my dream job, following my curiosity.

Next, I want to thank Professor Lars-Erik Malmberg and Dr. Pei-Hsin Li for your contributions and collaboration on the study as coauthors. It has been a pleasure to cooperate with such sharp minds, beautifully complemented by your kindness, and I truly look up to you both. Furthermore, conducting this study would not have been possible without the help of my colleagues, the teachers of the laboratory course, Dr. Pia Damlin, Dr. Henri Kivelä, Dr. Heidi Korhonen, Dr. Anssi Peuronen, Dr. Päivi Poijärvi-Virta, and Dr. Mikko Salomäki, as well as Laboratory Assistant Tiina Buss. Thank you all for your collaboration. I would also like to express my gratitude to all students participating in this research. Thank you for taking the time to respond to the questionnaires, particularly when you may have felt overwhelmed, perhaps due to the mistakes you encountered. The work is dedicated especially to them.

I feel fortunate to have had the opportunity to work alongside multiple talented and kind researchers. First, I would like to thank the entire staff of the Department of Chemistry for making it feel like a place where I truly belong. I also would like to express my gratitude to the doctoral researchers at TRILA, Arka, Heidi, Heli, Jakob, Marika, Meiling, Prince, Roy, Santeri, Simo, Sonja, Timi, and Umar, with whom I have had the pleasure of sharing this journey. I also want to extend my thanks to my other wonderful TRILA colleagues, Antti, Joonas, Jo, Jake, Kati, and many others. Thank you to my extended network – the EDUCA Flagship researchers, the members of the STEM Education Research Seminar, and the ESERA colleagues and friends, particularly my brilliant mentors from the Doctoral School, Betzabé and Bob – for making me feel like I am part of a community regardless of where I am.

Henna, I am forever grateful for your peer support and friendship through this journey. Thank you for not only sharing my love for science education but also sharing the numerous moments of celebration, frustration, deep flow, and laughter with me. My special thanks also go to my dear chemist friends, Ammi, Evita, Otto, and Saara. Especially, Ammi, for always believing in me, as you earned these special thanks through *Papupeli* already years ago. Thank you, Raxu and Stella, for sticking with me all these years and phases of life; I never cease to feel excited and grateful for getting to share my life updates with you.

To my family, thank you for always fostering my curiosity and for meeting my passionate – even overzealous – talks about science with such a genuine interest, especially you, Ilkka. Thank you, Mom, for emphasizing mastery over performance and raising us with such empathy and wisdom. Thank you, Hippo, for bringing joy and balance to my life, and, of course, for constantly trying to contribute to this thesis by standing on my keyboards. And finally, my deepest thank you to my husband, Henkka, for everything. There is no way in the world I could have survived this without you (and especially your cooking). Thank you for sharing my ambition and determination while also softening my world with your love.

4.2.2026
Reetta Kyynäräinen

REETTA KYYNÄRÄINEN

A dedicated science education researcher with a strong interest in educational psychology. Passionate about exploring how challenges, such as encountering mistakes and failure, as well as experiencing difficulties and negative emotions, influence learning. Believes in the importance of balancing struggle and success, and that meaningful learning emerges through effort and perseverance.

Table of contents

Abbreviations

CVT	Control-Value Theory
EMA	Ecological momentary assessment
ICC	Intraclass correlation coefficient
IER	Integrative emotional regulation
MLM	Multilevel modeling
MLR	Maximum likelihood for robust standard error
(M)SEM	(Multilevel) structural equation modeling
OLM	Optimal learning moment
SEVT	Situated Expectancy-Value Theory
STV	Subjective task value
WLSMV	Weighted least square mean and variance adjusted
ZPD	The zone of proximal development

List of original publications

This dissertation is based on the following original publications, which are referred to in the text by their Roman numerals:

I Kyynäräinen, R., Vilhunen, E., & Vesterinen, V.-M. How making mistakes shapes students' situational engagement in chemistry laboratory? *International Journal of Science Education*, 2024; 1–21. https://doi.org/10.1080/09500693.2024.2439142

II Kyynäräinen, R., Vilhunen, E., Li, P.-H., Laakso, M.-J., & Vesterinen, V.-M. Students' emotional responses to mistakes: An ecological momentary assessment study in university chemistry laboratory. [Manuscript submitted for publication].

III Kyynäräinen, R., Malmberg, L.-E., Vilhunen, E., Laakso, M.-J., & Vesterinen, V.-M. Failing forward in chemistry laboratory courses: The impact of engagement and mistakes during pre-lab activities on students' situational engagement. *Chemistry Education Research and Practice*, 2026; 27(1); 45–60. https://doi.org/10.1039/D5RP00231A

1 Introduction

Without mistakes, can genuine learning occur? In their review study of the differences between learning and performance, Soderstrom and Bjork (2013) argue that learning and performance are often misinterpreted as the same thing in educational contexts, as learning tends to be appraised through performance. However, performing perfectly without any mistakes demonstrates one's current competence rather than relatively permanent changes in behavior or knowledge, which support long-term retention and transfer, that is, learning (Kipnis, 2011; Soderstrom & Bjork, 2013). In contrast, momentarily unoptimized performance, including more mistakes, can, in fact, promote long-term learning (Keith & Frese, 2008; Loibl & Leuders, 2019; Mera et al., 2022; Metcalfe, 2017; Soderstrom & Bjork, 2013). Particularly motor learning, which is one of the central learning goals of laboratory education (P. A. Kirschner, 1992), benefits from distributing practice and increasing its variability, typically also increasing the frequency of mistakes (Soderstrom & Bjork, 2013). Hence, this study posits that mistakes are markers of learning opportunities within the context of the chemistry laboratory.

Furthermore, scientific knowledge is constructed through persistent trial and error, making mistakes an intrinsic part of its nature (Allchin, 2012, 2020; Firestein, 2016; Kipnis, 2011; Nunes et al., 2022; Simpson & Maltese, 2017). Prior research also suggests that the discrepancy between one's expectations and the actual outcome is essential for learning (Metcalfe, 2017). As such, learning from mistakes extends beyond learning how to avoid them in the future and is a specific learning phenomenon in itself (Frese & Keith, 2015; Tulis & Dresel, 2025). Considering these notions, it is surprising that investigating learning from mistakes and their role in learning processes remains a relatively new practice in educational sciences, particularly in the field of science education (Steuer et al., 2025).

Previous studies suggest that students' goals and behavior in chemistry laboratory courses are primarily driven by the affective learning domain, making the affective outcomes of mistakes an important antecedent of their learning (DeKorver & Towns, 2015; Keen, 2021). There is still a deficiency of research examining students' situational affective responses to mistakes (Schmid et al., 2025), especially beyond the field of educational psychology, and particularly in the chemistry laboratory (Keen & Sevian, 2022; Schechtel & Bongers, 2026). Previous research proposes that although students have rather stable beliefs about whether they can learn from their mistakes (Schmid et al., 2025; Tulis et al., 2018; Tulis & Dresel, 2025), their reactions to specific mistakes are more malleable, situational, and contextual (Keen, 2021; Schmid et al., 2025; Soncini et al., 2025; Tulis & Dresel, 2025). Thus, the phenomenon should be approached using data collection methodologies that enable capturing momentary and context-specific fluctuations in students' affective experiences, such as the ecological momentary assessment (EMA) design (Carson et al., 2010; Kitterød & Lyngstad, 2005; Sinatra et al., 2015).

Therefore, this thesis aims to investigate students' situational affective responses to mistakes in a chemistry laboratory course, while considering the influence of individual, situational, and contextual factors on students' experiences. The practical aims are to broadly inform practices in chemistry education, and more specifically, on how to support students in dealing with mistakes. The thesis comprises three interrelated sub-studies (referred to as Study I, Study II, and Study III) examining the phenomenon from different angles. The research data for this study were collected from university students participating in their first chemistry laboratory course, through a background questionnaire and a set of EMA questionnaires, which provide repeated self-report data in situ (Sinatra et al., 2015).

Study I (Kyynäräinen et al., 2024) focuses on how mistakes impact students' situational engagement in the chemistry laboratory, Study II (Kyynäräinen et al., submitted for publication) examines students' emotional responses to mistakes, and both consider the role of individual and situational factors in shaping these affective constructs. Study III (Kyynäräinen et al., 2026) investigates whether students' affective experiences in the laboratory can be predicted by their antecedent experiences, for example, during pre-lab activities. Namely, Study III explores the role of students' mistakes and their situational engagement during pre-lab activities on their situational engagement in the subsequent laboratory sessions. All research questions are addressed using quantitative analyses, including various applications of multilevel structural equation modeling (MSEM).

This dissertation consists of six chapters. Chapter Two presents the theoretical framework of the work, focusing on chemistry laboratory education, affective learning, and mistakes, concluding with a section presenting the key perspectives adopted, aims of the thesis and the overarching research questions. Chapter Three focuses on the methods, opening with a summary of the methodology, after which the context, participants, data collection designs, measures, analytical approaches, ethical considerations, and a statement on the use of artificial intelligence are presented in more detail. Then, the three original publications are briefly summarized in Chapter Four. The results are discussed in Chapter Five, which addresses the main findings, theoretical and methodological reflections, as well as some practical implications. Finally, the thesis ends with a concluding summary in Chapter Six.

2 Theoretical framing

The key focus of this thesis is students' *situational* affective responses to mistakes. Here, a situation is understood as a brief period of time during which individuals take part in learning activities. These activities include pre-lab activities in an online learning environment, as well as laboratory activities, such as conducting experimental procedures and interpreting the data obtained. In this study, students' affective experiences are measured approximately one hour apart, thus reflecting either a triggered situational affect, defined as a fleeting psychological state resulting from short-term changes in cognitive and affective processing, or a maintained situational affect, defined as a psychological state that involves focused attention through re-engaging with content that had previously triggered one's attention (see Hidi & Renninger, 2006; Renninger & Hidi, 2019).

Mistakes interplay with cognitive and affective dimensions of learning, as they can act as prompts for cognitive learning (e.g. Kapur, 2008; Kapur, 2016; Kapur & Bielaczyc, 2012; Keen, 2021; Loibl & Leuders, 2019; Trueman, 2014), and they are known to shape students' affective experiences (e.g. Käfer et al., 2019; Reindl et al., 2020; Steuer et al., 2025; Tulis et al., 2018; Tulis & Ainley, 2011). In addition to these, social norms and the sociocultural context can impact students' individual responses to mistakes across various contexts, including the chemistry laboratory (Keen & Sevian, 2022; Sharabi & Roth, 2025; Soncini et al., 2022). Accordingly, neither their social nor individual dimensions should be overlooked (Keen & Sevian, 2022; Sharabi & Roth, 2025; Soncini et al., 2022; Steuer et al., 2025). Thereby, along the lines of Pekrun (2006; 2024) in his Control-Value Theory (CVT), Eccles and Wigfield (2020) in their Situated Expectancy-Value Theory (SEVT), and Schneider and colleagues' theory of optimal learning moments (OLM) (2016), this thesis adopts a primarily cognitive-motivational framework, yet sociocultural aspects of learning are still considered.

In this chapter, relevant theoretical concepts are addressed one by one. First, the context of this research, that is, higher education chemistry laboratory courses, is introduced. This section is followed by another, shedding light on the affective learning dimension. In it, affective constructs that are focused on in this study, including emotions, engagement, and motivational factors, are described, and their role in learning in chemistry laboratories is elucidated. Third, the concept of mistakes is introduced, including its definition and categorizations of mistakes, as well as their role in learning. Finally, the last section focuses on the present study, establishing the key theoretical assumptions adopted and the aims of this thesis.

2.1 Chemistry laboratory education

This section focuses on the context of the research, namely, chemistry laboratory education. In the first subsection, the commonly identified learning objectives and outcomes of the undergraduate chemistry laboratories are introduced. Then, with the support of previous research, the second subsection frames chemistry laboratories as affective learning environments. This framing is built on later in this chapter, as subsection '2.2.4 Affective learning in the chemistry laboratory' introduces previous findings on students' affective experiences in chemistry laboratories.

2.1.1 The objectives of chemistry laboratory education

Laboratory work is deeply rooted in chemistry education, particularly at the higher education level (Agustian et al., 2022; Seery et al., 2024). Despite its distinctive nature, its importance has been debated regularly (see e.g. Agustian et al., 2022; Bretz, 2019; Hawkes, 2004; Hofstein & Lunetta, 2004; P. A. Kirschner, 1992; Seery et al., 2024). Particularly, the resource-intensive nature of chemistry teaching laboratories has frequently been presented as an issue, also challenging their importance (Bretz, 2019; Hawkes, 2004). In the ongoing discourse, chemistry teaching laboratories have been framed as spaces for learning to do science, arguing for their unique significance (Agustian et al., 2022; Seery, 2020).

Furthermore, in recent years, several significant accomplishments of laboratory education have been identified (Agustian et al., 2022; Seery et al., 2024). These include experimental competencies, disciplinary learning, higher-order thinking skills, epistemic learning, transversal competencies, and affective learning (Agustian et al., 2022; Seery et al., 2024). Thereby, chemistry laboratories create complex, embodied learning environments that are characterized by integrating knowledge, skills, and attitudes, and require one to coordinate qualitatively different elements (Agustian, 2022; Agustian & Seery, 2017).

In that regard, science (or chemistry) education could be attributed to three dimensions, including learning science, learning about science, and learning to do science (Hodson, 2014). According to Hodson's (2014) conceptualization, *learning science* encompasses the acquisition of conceptual knowledge and should be aligned with the content knowledge objectives of the science curricula. *Learning about* *science* involves familiarizing oneself with scientific practices and methods, learning about the history and development of science, as well as identifying the role of science in society. Finally, *learning to do science* involves using and adopting the scientific practices and methods, studying phenomena, testing and improving one's understanding, problem-solving, and following one's interests.

All three dimensions should be manifested in chemistry laboratory education (Agustian, 2020, 2022; Seery et al., 2024). This is illustrated in Figure 1, where the central accomplishments of chemistry laboratory education, presented by Agustian and colleagues (2022), have been embedded in Hodson's (2014) threefold framework.

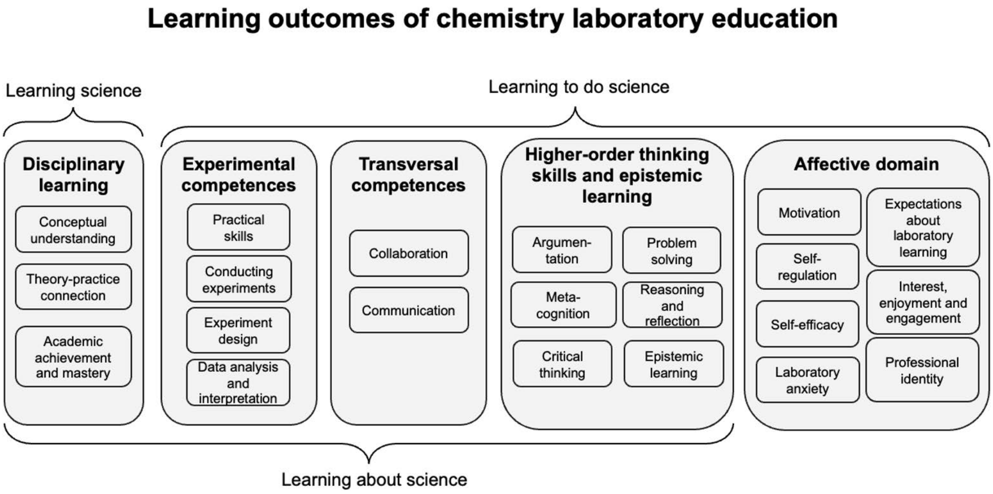

Figure 1. The learning outcomes of chemistry laboratory education, according to Agustian and colleagues (2022), embedded in Hodson's (2014) framework for the three key objectives of science education.

The objective of learning conceptual knowledge through laboratory work ought to be clear to students, as not being aware of this could lead to, for example, students coming to believe that science does not work or that one needs to know the result in advance (Hodson, 2014). In contrast, Allchin (2012) argues that on some occasions, it is vital to teach students how science *does not* work, providing them with a window into learning about science. This is well manifested in the mistakes students encounter in the chemistry laboratory, as they could be utilized to provide further conceptual understanding (e.g. Kapur, 2008), and to learn about the epistemology of science (Allchin, 2012). Nevertheless, perhaps the most fundamental dimension in laboratory education is the learning to do science aspect (Agustian, 2022; Seery, 2020). A focus on this dimension undermines the objective of obtaining the 'right answer', focusing students' attention on the complexities of scientific investigations, including refining, adjusting, and modifying strategies (Hodson, 2014). Therefore, doing science should act as a trigger also for learning about science (Hodson, 2014).

Regardless, previous research demonstrates that even though university students tend to subscribe to the idea that science is tentative (Agustian, 2019), they still focus on finishing the work, getting the ‘right answer’, and avoiding mistakes in chemistry laboratory courses (DeKorver & Towns, 2015; Keen & Sevian, 2022; Schechtel & Bongers, 2026). Students may even strongly believe that if they could follow the procedure strictly and avoid human error, they could completely avoid making mistakes (Schechtel & Bongers, 2026). This is not, of course, possible, regardless of how well designed the laboratory activity is (Schechtel & Bongers, 2026). This kind of emphasis could plausibly be shifted through highlighting the underlying learning objectives of learning to do science and learning about science (Allchin, 2012; Hodson, 2014). Indeed, mistakes are an intrinsic part of chemistry laboratory education due to the embodied nature of experimental work (Agustian et al., 2025b; Allchin, 2012; Keen & Sevian, 2022). This remains true, even if the experiments are of a lower level of open inquiry (Allchin, 2012; Schechtel & Bongers, 2026), which is the case in most modern laboratory instruction (Agustian et al., 2022; Buck et al., 2008).

Typically, chemistry laboratory courses consist of pre-laboratory activities (‘pre-labs’), followed by an instructional hands-on experiment in the laboratory environment (Agustian & Seery, 2017). The primary objective of pre-labs has traditionally been introducing relevant chemical concepts through pre-laboratory lecture, quiz, or discussion, but more recently, objectives such as introducing experimental techniques through videos, simulations, or safety information, and equipping students for the affective experiences in the laboratory by fostering confidence, motivation, or reducing anxiety, have been distinguished (Agustian & Seery, 2017; Chu & Leighton, 2019; Rayment et al., 2023). Seery and colleagues (2024) also argue that pre-labs could pinpoint the intended goals for the laboratory experiment, enhancing constructive alignment and directing students’ attention to relevant objectives. According to previous research, enacted learning experiences in the laboratory are indeed intensely framed by one’s expectations – what one anticipates thinking and feeling will partially determine the reality (Galloway & Bretz, 2015).

2.1.2 Chemistry laboratories as affective environments

The multidimensional nature of laboratory work stimulates multiple learning domains, but for a long time, the affective domain of laboratory work has remained neglected (Galloway et al., 2016; Seery et al., 2019). The affective learning domain includes psychological constructs such as attitudes, values, beliefs, moods, emotions, interest, and motivation (see e.g. Agustian et al., 2022; Blanco et al., 2010). Only relatively recently, research has started to focus more and more on the affective experiences related to learning in the laboratory, as its role in, for instance, students' goal setting (DeKorver & Towns, 2015; Keen & Sevian, 2022), thoughts and behavior (Galloway et al., 2016; Galloway & Bretz, 2015), and nurturing positive attitudes toward science (cf. Agustian et al., 2025b; Agustian & Seery, 2017; Bowen, 1999) has been recognized.

Indeed, previous research (DeKorver & Towns, 2015; Galloway et al., 2016; Keen & Sevian, 2022) suggests that the affective domain is the primary driver of students' learning goals in the chemistry laboratory. Students' affective needs can even compromise cognitive or psychomotor learning: for example, the goal of feeling good by finishing experiments early can overrun students' original intentions and learning goals of spending time practicing techniques and understanding concepts (DeKorver & Towns, 2015). Thereby, understanding students' affective experiences in the chemistry laboratory is highly relevant, as they may shape not only the affective goals students set for themselves but also their behavior and actions (DeKorver & Towns, 2015; Galloway et al., 2016).

In light of this current discourse on chemistry laboratory education, chemistry teaching laboratories are increasingly being redefined as affective environments (e.g. Agustian et al., 2025a; DeKorver & Towns, 2015; Galloway et al., 2016). Amid calls for curriculum reform, chemistry laboratory education is also transforming (Keen & Sevian, 2022; Seery et al., 2024). This transformation could be viewed as an ongoing reform that places a greater emphasis on students' diverse learning experiences, affective dimensions, and multifaceted learning goals of undergraduate chemistry laboratory education (DeKorver & Towns, 2015; Galloway et al., 2016; Keen & Sevian, 2022; Seery et al., 2024).

2.2 Affective learning

As was described in the previous section, student learning in the chemistry laboratory involves cognition as well as affect (e.g. Galloway et al., 2016). Affective goals and experiences strongly influence students' behavior and actions in the chemistry laboratory, and thus, are crucial not only for the learning experience but also for learning outcomes (DeKorver & Towns, 2015).

This section defines and describes the affective constructs focused on in this study. Emotions, situational engagement, and motivational factors are first conceptualized in Table 1, and then addressed in more depth in respective subsections. Finally, some previous key findings on students' affective learning in the chemistry laboratory in general are highlighted. Furthermore, all studied constructs – emotions, situational engagement, and motivational factors – are linked to learning either specifically in chemistry laboratory contexts, more generally, or both.

Table 1. Conceptualizations of key affective constructs, and their relation to learning.

Term and key references	Conceptualization	Relation to learning
Emotion (Brun et al., 2016; Pekrun et al., 2018; Shuman & Scherer, 2013)	An affective construct involving multiple interrelated components: affective, cognitive, physiological, motivational and behavioral. Relatively short in duration, triggered by and directed toward specific objects.	Tightly intertwined with learning: 1) defines the related psychological processes and can either hinder or foster learning, and 2) can be triggered by the learning experience.
Situational interest (Hidi & Renninger, 2006)	A short, spontaneously motivating psychological state, related to cognitive and affective processing, triggered by external factors and sustained through personal involvement or meaningfulness.	A precondition for meaningful engagement, can foster learning.
Flow (Csikszentmihalyi, 1990; Shernoff et al., 2014)	A situation-specific response, characterized by higher-than-average levels of both challenge and skill. So deeply engaging that it makes time lose its temporal boundaries, momentarily even suspending human needs.	Can facilitate learning by supporting conditions conducive to it, such as focused concentration, persistence, and enjoyment.
Situational engagement (Schneider et al., 2016; Tang et al., 2025)	A psychological state in relation to a learning task, a dynamic construct that is experienced in instances called *optimal learning moments.* Characterized by high situational interest supplemented by higher-than-average perceptions of their competencies and task difficulty (i.e., a flow state).	Results in concentration, efficacy, enjoyment, happiness, and success. Supposedly fosters meaningful learning.
Motivation (Csikszentmihalyi, 1990; Deci & Ryan, 1985; Dweck, 1986; Eccles & Wigfield, 2020; Hidi & Renninger, 2019)	Generally, a domain-specific, individual, affective disposition toward a certain subject, task, or activity, reflected as a driving force to do something.	Aligns behavior and choices with one's goals, can facilitate meaningful learning.

2.2.1 Emotions

Emotions are affective constructs that involve multiple interrelated components: on top of affective, also cognitive, physiological, motivational, and behavioral (Brun et al., 2016; Pekrun et al., 2017). They are relatively short in duration, triggered by a specific stimulus and directed toward a specific object (Pekrun et al., 2018; Shuman & Scherer, 2013). They are important preconditions for learning, as the nature of an emotional state defines the related psychological processes (Corwin et al., 2022; Pekrun, 2006; Pierson et al., 2023). Reciprocally, different learning activities and episodes can also trigger certain emotions, which, in turn, shape the learning experience (Beymer et al., 2021; Murphy et al., 2019).

Emotions can be viewed through several lenses and they can be categorized based on multiple factors (Pekrun, 2024; Pekrun et al., 2018). First, emotions are commonly classified according to their valence, which reflects the generally perceived comfort associated with experiencing the specific emotion (Pekrun et al., 2018). Another commonly considered dimension is the arousal of the emotion, describing how the emotion impacts one's physiological activity, either preparing them for a quick reaction or putting them to rest (Ketonen et al., 2023; Pekrun et al., 2018). These two factors can be used to further construct four categories: positive activating, positive deactivating, negative activating, and negative deactivating emotions (Pekrun et al., 2018; Russell, 1980). Typically, positive activating emotions relate to and are considered to foster learning, while the distinction between other types of emotions and learning is more complex (D'Mello et al., 2012; D'Mello & Graesser, 2011; Pekrun, 2006; Pekrun et al., 2018; Schneider et al., 2016). Experiencing adequate levels of some negative emotions, such as anxiety and confusion, in terms of intensity and duration, can promote learning (D'Mello et al., 2012; D'Mello & Graesser, 2011; B. Schneider et al., 2016), whereas experiences of negative deactivating emotions, such as boredom, can be detrimental for learning (D'Mello & Graesser, 2011; Goetz et al., 2014; Pekrun et al., 2010). The association between experiencing deactivating positive emotions and learning is more ambivalent (Pekrun, 2006). Nevertheless, learning enhancing emotions are typically activating emotions, emphasizing the key role of student agency in the learning process (D'Mello & Graesser, 2011; Pekrun et al., 2018; B. Schneider et al., 2016).

In addition to these two dimensions – valence and arousal – emotions can be divided into state and trait emotions (Pekrun et al., 2018). State emotions arise as situational responses to specific stimuli, while trait emotions reflect an individual's habitual, more stable disposition to experience a certain state emotion across similar situations (Pekrun et al., 2018). For example, experiencing anxiety as a response to making a mistake would be considered a state emotion, while the tendency to always experience anxiety when making mistakes would indicate a trait emotion. Previous research suggests that students' domain-specific interest (a more trait-like disposition[1]) is built upon repeated experiences of situational interest (state-like experience) (Hidi & Renninger, 2006; Krapp, 2002). Similarly, on-task state emotions could translate into habitual, trait-like emotional responses to certain learning domains (see also Keller et al., 2025; Tulis & Ainley, 2011). Therefore, understanding students' situational responses to certain triggers, such as making mistakes, can provide valuable information about what types of affective-motivational and action-adaptive outcomes and beliefs about mistakes they internalize.

Along these lines, compared to students' trait-like dispositions, their situational emotions may not be as strongly influenced by individual characteristics (Goetz et al., 2013; Tulis & Ainley, 2011). This could be explained by some individual characteristics being linked to certain stereotypes, which may contribute to, for instance, students overestimating their habitual, trait-like anxiety (Goetz et al., 2013). Consequently, approaching students' emotional experiences through situational measures can be less biased by such stereotypes.

Expanding on these distinctions, Pekrun's (2006, 2024) Control-Value Theory (CVT) explains how individuals' emotions emerge in achievement settings and beyond (see Figure 2). It proposes that emotional experiences are cognitively mediated, determined by an individual's appraisals of control and value. Thus, emotions depend on individuals' adaptive interpretations of their competencies to manage the situation (Pekrun, 2006, 2024). The updated, generalized CVT posits that emotions relate to a specific trigger, an object focus, yet they are holistic and can relate to various antecedents, for example, success and failure outcomes (achievement emotions), building knowledge (epistemic emotions), social relations (social emotions), or simply existing (existential emotions) (Pekrun, 2024). According to the CVT framework, which is adopted for this study, individual, situational, and contextual factors are important determinants of all types of emotions in academic settings.

1 Hidi and Renninger are clear that they are not describing trait-like motivation in the later phases of interest development, because, as they note (see Renninger & Hidi, 2022), interest, even when well-developed, may fall off or go dormant without challenge.

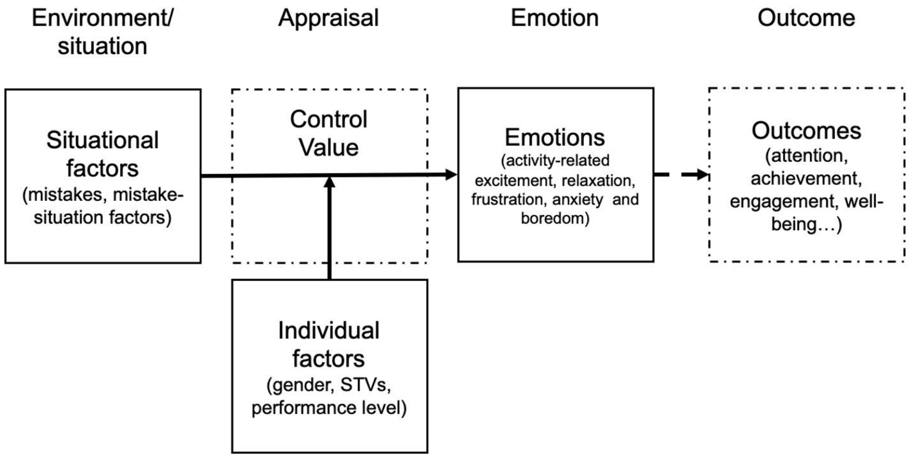

Figure 2. The dynamics focused on in Study II, embedded in Pekrun's Control-Value Theory framework (2026). The variables and associations presented in dotted boxes or with dotted arrows are not measured in this study.

In this thesis, the primary focus is on students' achievement emotions that relate to ongoing laboratory activities (Pekrun, 2026; 2024). Although these emotions primarily reflect one's current emotional states, they can be either more retrospective or prospective, oriented towards past experiences or future expectations (Pekrun, 2024). For example, anxiety may also be linked to students' appraisals of a potential achievement outcome of failure, reflecting their worries and fears of failure that arise in response to their mistakes (Pekrun, 2024).

Finally, in learning contexts, it is essential to consider not only emotions but also the underlying process of emotional regulation (Mega et al., 2014; Pekrun et al., 2002; Reindl et al., 2020; Sharabi & Roth, 2025). By fostering positive emotions (Liu et al., 2025) and regulating negative emotions to adequate levels (D'Mello et al., 2012; D'Mello & Graesser, 2011; Salmela-Aro & Upadyaya, 2014), further learning can be achieved. Emotional regulation practices impact how individuals cope with challenging situations, such as making mistakes (Corwin et al., 2022; Sharabi & Roth, 2025). However, while emotional regulation reflects intra-individual processes, it can also be social and affected by interaction with others (Keen & Sevian, 2022) Ideally, students would engage in integrative emotional regulation (IER), which is considered the most mature and adaptive form of regulation, characterized by accepting, affirming, and taking interest in one's affective experiences without avoidance, judgment, or distortion (Ryan et al., 2016; Sharabi & Roth, 2025). Such regulation can enhance students' meta-affective learning, where initially negative affect is reappraised and turned into a positive meta-affect (Pekrun et al., 2018; Radoff et al., 2019; Sharabi & Roth, 2025). This could happen, for example, in a situation where the initially negative anxiety or stress indicates a learning opportunity, leading to the reappraisal of the emotions and ultimately reframing it as a positive experience.

2.2.2 Situational engagement

Engagement is typically characterized as an affective construct, but it can also contain other dimensions, such as cognitive and behavioral ones (Lawrie, 2023; Murphy et al., 2019; Sinatra et al., 2015). It reflects active involvement in a task, encompassing, for example, enjoyment in terms of the affective dimension, psychological investment in terms of cognitive engagement, and exerting effort and concentrating in terms of behavioral engagement (Lawrie, 2023; Murphy et al., 2019; Sinatra et al., 2015). There is high domain-specificity in engagement, and thus, it is tightly intertwined with the context (Lawrie, 2023; Sinatra et al., 2015). Furthermore, it has been referred to as *the holy grail of learning*, as it has been linked to positive learning outcomes, such as higher motivation and academic achievement (Sinatra et al., 2015)

Engagement can be studied at the micro- or macro-level, portraying it either as an individual state in relation to a situation or a learning task, or as a collective state at the class, course, school, or community level (Sinatra et al., 2015). In this study, the focus is on the first – microlevel engagement within an individual – in order to capture how individuals tend to react to mistakes. This individual engagement can further be divided into habitual, stable trait-like engagement and momentary, dynamic state-like engagement (Salmela-Aro et al., 2016; B. Schneider et al., 2016; Tang et al., 2025). This study focuses on the latter, viewing engagement as a dynamic construct that can be shaped through learning activities and episodes, such as making mistakes.

On that account, the situational engagement paradigm is adopted in this study, and high situational engagement is conceptualized as optimal learning moments (OLM) (B. Schneider et al., 2016; Tang et al., 2025). This OLM framework integrates interest, perceived competence, and task difficulty (B. Schneider et al., 2016; Tang et al., 2025). It builds on and combines situational interest (Hidi & Renninger, 2006; Krapp & Prenzel, 2011) and the concept of flow (Csikszentmihalyi, 1990; Schmidt, 2010), postulating that learning should be not only interesting, but also sufficiently challenging. Situational interest – perceived as an important precondition for meaningful engagement and learning (Renninger & Bachrach, 2015) – reflects a short, spontaneously motivating psychological state that is triggered by external factors and sustained through personal involvement or meaningfulness (Hidi & Renninger, 2006). If sustained, it may help students focus on the task and invest effort, even when the task feels challenging (Hidi & Renninger, 2006). However, situational interest may fade away quickly if the student does not feel competent in completing the task (Hidi

& Renninger, 2006; Järvelä & Renninger, 2014) or if they are not adequately challenged (Renninger & Hidi, 2022). Consequently, situational interest could be supplemented by flow. In contrast, flow is a situation-specific response, characterized by higher-than-average levels of both challenge and skill (Csikszentmihalyi, 1990). The flow state is so deeply engaging that it makes time lose its temporal boundaries, momentarily even suspending the human needs (Csikszentmihalyi, 1990). Thereby, optimal learning theory defines high situational engagement as instances where students simultaneously experience high interest, high skills, and high challenge (B. Schneider et al., 2016; Tang et al., 2025).

Experiencing OLMs is assumed to promote learning, although there is yet no empirical support for a direct relationship between OLMs and heightened learning outcomes (B. Schneider et al., 2016; Tang et al., 2025). Nevertheless, this relationship could be mediated by, for example, students' self-regulatory processes (Heikkinen et al., 2025), and the use of efficient learning strategies (W. Lee et al., 2014; B. Schneider et al., 2016). Importantly, experiencing high situational engagement and OLMs could also be associated with broader affective outcomes, such as experiencing concentration, enjoyment, efficacy, and success (B. Schneider et al., 2016; Tang et al., 2025), and perhaps developing sustained engagement or motivation (Blumenfeld et al., 2004; Hidi & Renninger, 2006).

Finally, the elements of situational engagement (i.e., interest, skill, and challenge) can be allocated to different learning domains (cf. Lawrie, 2023). For example, situational engagement can overlap with cognitive engagement (see Agustian, 2022; Lawrie, 2023) in terms of the demand for high enough challenges. Concurrently, it relates to affective engagement through interest and perceived competence (i.e., skill) (Agustian, 2022; Lawrie, 2023). Moreover, interest, conceptualized as a cognitive, affective, and motivational state, considers cognition and affect as synergistic, with shifts in their present emphasis across different phases of its development (Hidi & Renninger, 2006), and a similar conceptualization could be applied to engagement. Finally, the embodied nature of laboratory work rather automatically activates the psychomotor domain (Galloway & Bretz, 2015). Thereby, experiences of high situational engagement in the chemistry laboratory may also enable meaningful learning that combines thinking, feeling, and acting – activating a number of cognitive, affective and behavioral processes that can promote learning (Galloway et al., 2016; Galloway & Bretz, 2015; Novak, 2010).

2.2.3 Motivational factors

Motivation can be defined in several ways, depending on the underlying theory. Yet, it is generally viewed as a domain-specific, individual, affective disposition toward a certain subject, task, or activity, and it drives oneself to act (Bolte et al., 2013;

Csikszentmihalyi, 1990; Deci & Ryan, 1985; Dweck, 1986; Eccles & Wigfield, 2020; Hidi & Renninger, 2019). Across the major motivational theories, it can be understood to relate to the context, such as environment or situation (Urhahne & Wijnia, 2023). Like engagement, motivation can also be viewed as a dynamic construct, fluctuating over time (e.g. Tulis & Fulmer, 2013). However, more stable motivational traits and beliefs can impact other dynamic processes related to learning, such as students' emotions (Pekrun, 2006).

A contemporary motivational theory, namely Eccles & Wigfield's (2020) Situated Expectancy-Value Theory (SEVT), postulates that students' choices regarding activities are shaped by their subjective valuing of them, and these subjective task values (STVs) are, in turn, partially determined by their expectancies of success or failure. These assumptions align with Pekrun's (2006; 2024) CVT, which posits that students' prospective or retrospective appraisals of success and failure can shape their control and value beliefs related to specific activities, and they can further impact students' emotional experiences. Consequently, in this thesis, Berweger and colleague's (2022) interpretation is followed, and these theoretical assumptions are combined to examine the role of motivational factors in shaping students' dynamic affective reactions to mistakes. Even though there are prior findings indicating that a general "subject value" may not be linked to students' emotional responses to failure (Tulis & Ainley, 2011), the more specific STVs are viewed as plausible determinants of students' emotional responses to making mistakes in this study.

Finally, as motivation and STVs are known to be highly contextual, they should be examined in consideration of a specific learning domain (Wigfield & Eccles, 2023). Previously, students' domain-specific utility and cost values have been associated with their emotional experiences (Berweger et al., 2022; Pekrun et al., 2018). Utility value reflects the individual's disposition to view activities as means to an end and beneficial for their future ambitions, rather than important in themselves, whereas cost value is conceptualized as emotional costs related to learning, reflecting the perceived stressfulness or exhaustion of the activities (Eccles & Wigfield, 2020). With regard to the domain-specificity, here, utility embodies the perceived *usefulness* of laboratory work, and cost represents the associated *burden* of laboratory work.

2.2.4 Affective learning in the chemistry laboratory

It is still a relatively new practice to study affective learning in the chemistry laboratory (Agustian et al., 2022; Galloway et al., 2016; Seery et al., 2019), although it is well-known that the context matters in shaping students' affective experiences (e.g. Keller et al., 2025; Pekrun, 2006; Pekrun et al., 2018). For example, the special place of laboratory education in chemistry and science education, as well as the complex nature of scientific inquiry, might induce several affective perceptions related to laboratory work, such as being nervous about handling chemicals or being excited to *do chemistry* (Galloway & Bretz, 2015; Schechtel & Bongers, 2026). Another example is laboratory anxiety, which can impact students' learning experiences substantially (Agustian & Seery, 2017; Bowen, 1999; Galloway et al., 2016; Schechtel & Bongers, 2026; Sesen & Mutlu, 2014). Students with laboratory anxiety possess more negative attitudes towards learning in the laboratory (Bowen, 1999; Rummey et al., 2019; Sesen & Mutlu, 2014), and may experience more anxiety on the situational level as well (see Keller et al., 2025). Laboratory anxiety, for instance, could be formed from previous negative experiences, entering a new and intimidating space, or being afraid to make mistakes (Schechtel & Bongers, 2026; Sesen & Mutlu, 2014). Therefore, it is important to understand what induces anxiety in students at the situational level and which students have the tendency to experience anxiety the most.

However, as Galloway and colleagues (2016) pointed out, supporting affective learning is a multifaceted matter. According to their paper, the trend in affective learning research has mainly concentrated on reducing students' anxiety and increasing their interest. This is even though learners' learning processes, let alone emotional experiences, can be very complex. Moreover, these experiences are intertwined with the act of doing science in the chemistry laboratory, and the complexity of the laboratory environment (Agustian et al., 2025b; Seery et al., 2019). Therefore, simply diminishing unpleasant experiences and introducing pleasant ones might not alone enhance meaningful learning, which integrates multiple other dimensions as well. This is significant, as mistakes, for instance, could trigger productive learning (Frese & Keith, 2015; Soderstrom & Bjork, 2013; Steuer et al., 2025), but based on previous research (e.g. Agustian et al., 2025b; Galloway et al., 2016; Schechtel & Bongers, 2026; Simpson & Maltese, 2017), are still consistently associated with negative affective experiences.

Students' affective experiences play a significant role in their goal-setting and behavior, and they can shape meaningful learning (DeKorver & Towns, 2015; Galloway & Bretz, 2015). In general, positive affective experiences within the chemistry laboratory context have been associated with enhanced cognitive processing, engagement in learning tasks, and ultimately, better academic outcomes (DeKorver & Towns, 2015; Galloway et al., 2016; Galloway & Bretz, 2015; Lawrie, 2023). Thereby, it is also crucial to point out that affective learning, indicated by, for instance, developing a positive relationship with laboratory work, building self-confidence, improving one's self-regulation skills, and fostering professional identity development, is – or at least should also be – an objective of undergraduate laboratory education and thus, an important learning outcome (Agustian et al., 2022).

Previous research suggests that students associate a wide range of emotions with chemistry laboratory work (Agustian et al., 2025b; Galloway et al., 2016). These emotions may depend on different dimensions of laboratory instruction (Seery, 2020), as experimental work has been associated with many positive emotions (Agustian et al., 2025b; Vilhunen et al., 2021), and computational phases with higher levels of negative activating emotions, such as anxiety, confusion, and frustration (Vilhunen et al., 2021). Positive emotions, as well as confusion, have been linked to higher scientific sensemaking abilities, whereas boredom relates to increased challenges or unwillingness to conduct scientific observations (Vilhunen et al., 2023). According to Schneider and colleagues (2016), such emotions that can increase students' ability to engage in scientific inquiry are established as learning enhancers, and they could potentially promote OLMs (i.e., instances of high situational engagement). Generally, OLMs are experienced more frequently in situations where students engage actively in working on problems, analyzing data, and modeling (e.g. Inkinen et al., 2019; Vilhunen et al., 2021).

Previous research has also examined situational engagement in relation to laboratory work, indicating that OLMs are rarely manifested in the laboratory (Atabek-Yigit & Senoz, 2023a). It is suggested that this is due to the low perceived challenge level of practical work, which has also been identified in other studies (Inkinen et al., 2019, 2020). However, developing explanations and solutions, and connecting theory to the ongoing practical experiment have been linked to experiencing OLMs (Atabek-Yigit & Senoz, 2023a; Inkinen et al., 2019, 2020).

Finally, personal characteristics, such as motivational factors, have been associated with students' situational engagement and emotions in the chemistry laboratory (Atabek-Yigit & Senoz, 2023a; Perez et al., 2014). In addition, contextual factors, such as the phase of the work (Habig et al., 2018; Sinatra, 2015; Vilhunen et al., 2021), as well as social factors, such as the form of support (Keen & Sevian, 2022), can play important roles in shaping students' affective experiences generally in science learning and more specifically in laboratory work. Therefore, the phenomenon should be examined in consideration of these aspects.

2.3 Mistakes

According to Vygotsky's sociocultural perspectives on learning, individual learning can be supported by operating at one's zone of proximal development (ZPD) (Vygotsky, 1978). This zone depicts the space between what an individual can independently accomplish and what they can do with the guidance and support of a 'more knowledgeable other', that is, a teacher or peers (Vygotsky, 19978). At the ZPD, an individual is operating at the edges of their knowledge and competence, and thus, mistakes are likely to occur (Vygotsky, 1978). The identification of the key role of mistakes in learning is not limited to the sociocultural learning paradigm, as the phenomenon has been addressed from, for instance, the lens of cognitive learning theories as well (see e.g., Kapur, 2008). To extend this to Piaget's framework of learning, mistakes signal cognitive conflicts and can prompt a change in learners' mental schemas (Piaget, 1929). Even in Skinner's (1953) behavioristic operant conditioning framework, mistakes are central, as unwanted behavior (such as mistakes) is reduced through punishment, and the desired behavior (success) is increased through reinforcement.

Thus, regardless of the underlying theory, making mistakes lies at the heart of learning (Soderstrom & Bjork, 2013). In particular, the embodied nature of laboratory work contributes to the inevitability of making mistakes as a part of the process (Agustian et al., 2025b; Corwin et al., 2022; Keen & Sevian, 2022), yet its role in chemistry laboratory education is under-researched and not properly understood (Agustian et al., 2025b; Schechtel & Bongers, 2026).

In this section, the phenomenon of making mistakes as a part of learning is addressed. First, mistakes are defined in relation to other similar constructs present in the literature. Second, some subcategories of mistakes are introduced, and finally, some previous findings are highlighted on how making mistakes (or similar constructs) may shape students' learning processes in chemistry education, science education or other disciplines.

2.3.1 Defining mistakes

Previous research does not always establish a clear division of different terms that describe the phenomenon of deviating from an expected trajectory (Simpson et al., 2020). Instead, words such as failure, error and mistake, sometimes accompanied by challenge, setback, struggle, obstacle and uncertainty, are used interchangeably to describe these events, regardless of the different tones or meanings these terms carry (see Table 2). Previous literature also very often lacks a definition of the term(s) used, although there are some attempts at defining, for example, failure or errors (Corwin et al., 2022; Firestein, 2016; Henry et al., 2019; Kipnis, 2011; Simpson & Maltese, 2017; Steuer et al., 2025; Tulis et al., 2016; Van Der Byl & Vredenburg, 2023). Nevertheless, trying to define and distinguish between these terms can, ironically, be perceived as doomed to fail (Allchin, 2012; Firestein, 2016). Yet in this study, the focus is specifically on mistakes, and accordingly, some distinctions should be noted – even though students, in the end, emotionally react to their own perception of *a mistake*.

In this subsection, mistakes are defined relative to the two other commonly used terms, failure and error. First, it should be noted that these terms are not synonyms. For example, mistakes do not necessarily indicate a failure, and failure can sometimes happen without a mistake (Frese & Keith, 2015; Steuer et al., 2025; Tulis et al., 2016; Van Der Byl & Vredenburg, 2023). Errors, on the other hand, function as a more technical subset of mistakes (Van Der Byl & Vredenburg, 2023). Thus, all errors can be perceived as mistakes, but not all mistakes are errors (Van Der Byl & Vredenburg, 2023).

An experience of failure is defined relative to an internalized and specific expectation, goal or objective set by, for example, the individual themselves or the environment (Corwin et al., 2022; Henry et al., 2019; Lutovac, 2019; Schechtel & Bongers, 2026; Tulis et al., 2016). It is characterized by not meeting the expectations, desired goals, or objectives (Schechtel & Bongers, 2026; Simpson & Maltese, 2017). Not meeting an external goal can also be interpreted as a failure, for example, in a social or societal context – yet an individual might not personally feel like failing if the goal has not been internalized (Frese & Keith, 2015; Lutovac, 2019; Tulis et al., 2016). Therefore, failure can be seen as partly subjective (Lutovac, 2019).

Mistake, on the other hand, may not have anything to do with an exact expectation, goal, or objective, but instead is characterized by a deviation from what is generally considered correct, a commonly accepted norm or appropriate, regardless of a specific goal (cf. Kipnis, 2011; Steuer et al., 2025; Tulis et al., 2016). Mistakes involve a misalignment with expected correctness or process, stem from a faulty plan, and could be attributed to some avoidable action (Kipnis, 2011; Reason, 1990; Van Der Byl & Vredenburg, 2023). Accordingly, mistakes are objective in relation to shared rules, or truths: even if you don't care about the outcome, a mistake can be recognized by anyone who understands the norms. Nevertheless, this study does not fully subscribe to the perception of mistakes as an objective phenomenon, as mistakes may be reported subjectively by students.

Furthermore, failure is inherently negative, as it represents a gap between intention and outcome (Cannon & Edmondson, 2005; Schechtel & Bongers, 2026; Simpson & Maltese, 2017). Mistakes, on the other hand, are less intrinsically negative, and their valence is more situational (Frese & Keith, 2015). Thus, students' affective responses to mistakes constitute a more situated phenomenon compared to their failure counterparts.

Mistakes and errors are more related, but again not synonyms. Some studies conceptualize mistakes as avoidable and errors as unavoidable ignorance (Kipnis, 2011). Mistakes are more human-centered, commonly associated with judgment (Kipnis, 2011; Van Der Byl & Vredenburg, 2023). In contrast, errors are more specific, involve factual inaccuracy and are typically measurable (Frese & Keith, 2015). For example, a judgment of call represents a mistake, but not an error, as there might not be any factual inaccuracy. The human-centeredness of mistakes is also potentially linked to stronger human reactions, including affective responses to these events. However, errors are sometimes conceptualized as stemming from a lack of knowledge, and as such a human error can be interpreted as a threat to self-concept, triggering even stronger affective reactions (Estrada et al., 2011; Schechtel & Bongers, 2026; Van Der Byl & Vredenburg, 2023). Nevertheless, errors, perceived here as essentially a subset of mistakes, are also considered when investigating affective responses to mistakes.

In the chemistry laboratory context, not obtaining the 'correct results' from the experiment has been given as an example of what students may perceive as failure, suggesting that their goal is to reach such results (Schechtel & Bongers, 2026). As described above, mistakes can be manifold, as any small step aside from the expected trajectory of the laboratory experiment can be understood as a mistake. For example, simply reading the volume of a solution incorrectly would be a mistake, despite later noticing and correcting it. An example of an error, in turn, could be using a flask with a scale of measurement with the wrong spacing between volumes and ending up with an incorrect volume.

Finally, given that students typically have the goal of finishing an experiment in the laboratory on time (DeKorver & Towns, 2015), mistakes that do not impact the completion are not necessarily failures (Schechtel & Bongers, 2026). Additionally, if the goal is to learn as much from the laboratory as possible, mistakes do not necessarily lead to failure but could potentially promote productive learning and contribute to reaching the goal (e.g. Kapur, 2008). In contrast, if students are assessed in the laboratory based on the correctness of their experiment, and an individual's goal is to score a high grade, a mistake can be detrimental to reaching the goal and interpreted as failure (Käfer et al., 2019; Schechtel & Bongers, 2026). Hence, context matters in how mistakes are interpreted.

Table 2. The distinctions between the commonly used terms: failure, mistake, and error.

	Failure	**Mistake**	**Error**
Definition	A misalignment between the outcome and the expectation, goal or objective	A deviation from what is generally considered a norm, correct, or appropriate	A technical subset of mistakes
Objectivity	Primarily subjective	Primarily objective	Objective
Valence	Inherently negative	Situational	Situational
Centeredness	Human-centered	Often human-centered	Fact-centered
Example	Scoring below one's goal in a test	Not noticing a test problem and missing it	Applying the wrong calculation method

2.3.2 Categorizing mistakes

Not all mistakes in the chemistry laboratory are similar (see Allchin, 2012; Blumenfeld et al., 1991: Simpson et al., 2020). Mistakes can occur during multiple phases of work, resulting in fundamentally different types of uncertainties. As a result, they may also influence students' affect in different ways. Previous research even argues that the spectrum of different types of mistakes is more worth thinking about than their definitions (Allchin, 2012). Indeed, utilizing classification structures allows organizing and situating the variety of mistakes that occur across authentic learning settings, for example, at different phases of scientific inquiry (Allchin, 2012). On that note, when investigating students' mistakes within science laboratories, distinctions between different types of mistakes should be made.

For one, students' mistakes can be categorized into careless mistakes, representing slips or lapses in execution, or mistakes that are caused by a lack of knowledge, skill, or understanding (Frese & Keith, 2015; Reason, 1990; Simpson et al., 2020). Second, particularly in the chemistry laboratory context, mistakes can be divided into experimental and conceptual ones (Allchin, 2012). Based on the contents of experimental and theoretical (i.e., conceptual) phases in the laboratory work (see Finne et al., 2023), experimental mistakes could contain unsuccessful execution of a chemical procedure, while conceptual mistakes might encompass, for example, mistakes in calculations, interpreting results, and understanding concepts. Experimental mistakes primarily fall within the psychomotor learning domain, whereas conceptual mistakes mainly fall within the cognitive domain. Allchin (2012) also introduces discursive mistakes as a third, distinct type, including mistakes such as incomplete reporting, mistaken credibility judgments, or public misconceptions of scientific results. However, the third mistake type is not included as a mistake category in this study, as it is more commonly manifested beyond the laboratory than within it.

These different types of mistakes may impact students' affective experiences in unique ways. For example, mistakes caused by a lack of knowledge, understanding, or skill indicate a cognitive conflict and could lead to conceptual change, which is often associated with negative affect (Chiu et al., 2019). It is also typical that students associate higher cognitive demands with theoretical phases of experimental work (Vilhunen et al., 2021). Thus, it could be hypothesized that conceptual mistakes are also perceived as more burdensome (Vilhunen et al., 2021). Regardless of these notions, previous research has not really established the role these different subcategories of mistakes play in shaping students' affect.

2.3.3 Mistakes and affective learning

Among the public discourse and the media, there are parallel narratives, either portraying (scientific) mistakes as embarrassing yet bemusing (Allchin, 2012), or stating that we need to fail – fail fast, fail often, and fail forward (Steuer et al., 2025). The first promotes negative stigma on mistakes, whereas the latter suggests that failure will trigger learning. However, when reduced to such oversimplified versions, neither claim is supported by research. First, research suggests that mistakes should be viewed positively as indicators of learning opportunities and that they can indeed lead to positive outcomes, such as productive long-term learning (e.g. Darabi et al., 2018; Keith & Frese, 2008; Metcalfe, 2017; Soderstrom & Bjork, 2013). Second, and conversely, it is rather naïve to assume that mistakes will conventionally lead to learning (e.g. Steuer et al., 2025). Nevertheless, such positive inducements can help in supporting students' affective learning by encouraging them to learn from their mistakes through cultivating positive beliefs about mistakes and fostering a mistake-friendly environment (Soncini et al., 2022; Steuer et al., 2013, 2025; Tulis et al., 2018; Tulis & Dresel, 2025).

Previous research suggests that learners' individual positive beliefs about mistakes (i.e., error beliefs) can foster positive affective responses and action-adaptive reactions to making mistakes (Leighton et al., 2018; Tulis et al., 2018). These positive beliefs, in turn, can be cultivated through a positive classroom (or laboratory) climate and sociocultural norms embracing mistakes (Kuhl, 2000; Leighton et al., 2018; Nunes et al., 2024; Peterson et al., 2025; Soncini et al., 2022; Steuer et al., 2013; Tulis & Dresel, 2025). This is referred to as the error climate of the learning environment (Steuer et al., 2013). In learning contexts with a positive error climate, mistakes are valued as natural parts of learning or framed even as beneficial for learning, providing useful feedback on learning activities (Ames & Archer, 1988, 1988; Käfer et al., 2019; Kuhl, 2000; Leighton et al., 2018; Metcalfe, 2017; Simpson et al., 2025; Tulis & Dresel, 2025; Wan et al., 2023). Additionally, common misconceptions are utilized as prompts for conceptual change and learning (i.e., productive failure [Kapur, 2008]), teachers can use erroneous examples in instruction, and mistakes are not used as a basis for negative evaluation (Dieterich et al., 2025; Käfer et al., 2019; Loibl & Leuders, 2019; McMillan & Moore, 2020; Tulis & Dresel, 2025). In addition to fostering positive beliefs about mistakes, this could also significantly reduce students' fear of failure and their capacity to learn from their mistakes (Blumenfeld et al., 1991; Leighton et al., 2018; Nunes et al., 2022, 2024).

Beyond interaction with teachers, the classroom or laboratory culture among peers can also impact students' emotional experiences (Keen & Sevian, 2022; Steuer et al., 2013). Keen and Sevian (2022) suggested that peers could be more likely to provide each other with socioemotional support in dealing with struggles, including mistakes, in the chemistry laboratory, whereas teachers may be more prone to focusing solely on the cognitive struggles. This emotional support can play a central role in students' individual integrative emotional regulation (IER), and thereby, adaptive coping practices to mistakes (Sharabi & Roth, 2025). Based on several studies, humor among peers can also be identified as a standard way of dealing with struggles or mistakes in the chemistry laboratory (Agustian et al., 2025b; Keen & Sevian, 2022; Lamminpää & Vesterinen, 2018). Perhaps in these situations, students accept, affirm, and take an interest in their negative affect through laughter – indicating that they are engaging in the IER processes (Ryan et al., 2016; Sharabi & Roth, 2025).

While the importance of affective support is emphasized, the role of cognitive support should not be overlooked (Allchin, 2012; Keen & Sevian, 2022). Cognitive support provided by the teachers is also associated with more positive beliefs about mistakes and more adaptive coping (Käfer et al., 2019; Leighton et al., 2018; Soncini et al., 2022; Tulis, 2013). Additionally, the idea behind productive failure aligns with these findings, as it postulates that to productively learn from mistakes, an instructional activity should follow (Kapur & Bielaczyc, 2012; Loibl & Leuders, 2019). However, a recent study suggests that not any kind of activity will do; simply focusing on mistake correction seems inefficient, while interaction and collaborative problem-solving on what the mistakes were, why they occurred, and how to avoid them in the future seems effective (Metcalfe et al., 2025). Accordingly, affective support becomes once again crucial, as the (lack of) emotional support provided by teachers may be associated with whether or not students decide to seek help from them (Leighton et al., 2018). Based on Leighton and colleagues' (2018) study, students who had higher trust in their instructors were more willing to openly discuss their mistakes with them. Hence, affective and cognitive support together could also foster meaningful learning in the laboratory, integrating affective, cognitive, and psychomotor dimensions (Galloway & Bretz, 2015; Novak, 2010).

In addition to these more external factors, individual characteristics can also play a role. Previously, motivational traits, mindset and goal-orientation have been associated with students' beliefs about making mistakes and coping with them (Henry et al., 2019; Meyer & Turner, 2006; Schechtel & Bongers, 2026; Tulis et al., 2016, 2018; Tulis & Fulmer, 2013). Growth mindset and mastery goal orientation seem to predict adaptive coping strategies, which, in contrast, have been associated with students' academic outcomes (Frese & Keith, 2015; Henry et al., 2019; Meyer & Turner, 2006; Huangfu et al., 2023; Tulis et al., 2018; Tulis & Fulmer, 2013). Additionally, previous studies suggest that males tend to react more adaptively to mistakes than females (Soncini et al., 2022), and that gender stereotypes can impact what the mistakes are attributed to(Di Battista, 2025). Nevertheless, relatively little is known about the individual factors shaping students' in-situ affective reactions to mistakes, particularly in the chemistry laboratory. In this context, prior research has identified that there are indeed individual differences among students in how they respond to mistakes; however, there is a need for a more comprehensive understanding of which individual factors may contribute to these differences (Agustian et al., 2025b; Schechtel & Bongers, 2026).

A very recent study focusing on students' affective responses to failure in an introductory chemistry laboratory course, approached through ethnography and student interviews, suggests that some students perceive making mistakes as a waste of time and effort, particularly because they were not assessed in the course in any way (Schechtel & Bongers, 2026). In conducting the study, the authors arrived at the understanding that in the context of their course, making generative and transformative mistakes as part of the learning process was not allowed, which is arguably true across many other similar contexts. This was due to several factors, including limited resources, such as time, being judged by instructors when encountering failure, or not knowing something, which resulted in stigmatizing and overwhelming experiences that students faced when they made mistakes. Similar conceptions of the chemistry laboratory can be found in other studies as well; for example, in Renninger and colleagues' (2018) case study, chemistry laboratories were introduced as an example of an unreasonably strict environment where everything feels like a procedure and alternative results are not allowed. As a result, students may feel compelled to pretend that they have not made a mistake even when they have (see Krajcik et al., 1998; Schechtel & Bongers, 2026).

Overall, there is limited knowledge on the affective outcomes of mistakes (Metcalfe, 2017; Schechtel & Bongers, 2026). Generally, making mistakes is associated with negative affect, such as experiencing negative emotions like anxiety and frustration (Agustian et al., 2025b; Frese & Keith, 2015; Galloway et al., 2016; Nunes et al., 2022; Schechtel & Bongers, 2026; Simpson & Maltese, 2017), and it has also been linked to a decrease in motivation (Tulis et al., 2016). In contrast, a study in the field of organizational psychology has shown that mistakes can be either motivating or demotivating, associated with different levels of engagement (Frese & Keith, 2015). That is, if the mistake is framed as an indicator of failure, being disruptive and frustrating, the individual will likely perceive it as demotivating, whereas mistakes indicating learning opportunities, accompanied by high task interest, can fuel persistence and motivation (Frese & Keith, 2015). Mistakes and particularly teacher support in navigating them have been mentioned as important variables in shaping students' situational engagement, also in science learning (B. Schneider et al., 2020) – yet there is a significant deficiency of empirical findings on these dynamics.

Moreover, studies in educational psychology have proposed that students who demonstrate adaptive self-regulation practices, as well as positive cognitive and affective reactions to mistakes, are also more likely to maintain their level of engagement (Käfer et al., 2019; Kuhl, 2000; Soncini et al., 2022; Tulis et al., 2016). However, particularly little is still known about students' situational affective responses, especially in authentic contexts, such as the chemistry laboratory, although previous studies suggest that students' reactions to mistakes are malleable and highly contextual (Keen, 2021; Schechtel & Bongers, 2026; Schmid et al., 2025; Soncini et al., 2025). There is a need for such knowledge because prior research suggests that what students think they feel (i.e., trait emotions) may not necessarily align with what they really feel (i.e., state emotions) (Bieg et al., 2014).

Encountering mistakes, as well as experiencing and overcoming negative emotions associated with them, is crucial in how students develop identity and resilience as scientists (Henry et al., 2019; Keen, 2021; Simpson & Maltese, 2017). Perhaps as an indication of this resilience, a study on scientists' perceptions of the role of failure in becoming a STEM professional (Simpson & Maltese, 2017) emphasized that some prefer completely avoiding the term failure and replace it with "success that has not happened yet" or "situations where things come out differently than expected". In another empirical study, students identified mistakes that do not compromise their goals as "acceptable failures" (Schechtel & Bongers, 2026). Considering these findings and our definition of mistakes in relation to failure, it could be suggested that both scientists and students more easily accept mistakes as part of their work compared to failure. Mistakes are, indeed, an intrinsic part of doing science, not the final outcome, and thus, they obtain a highly situational nature (Kipnis, 2011; Schmid et al., 2025; Soncini et al., 2025). This highlights the importance of understanding learners' situational responses to making mistakes, in addition to their general perceptions of failure or setbacks (Schmid et al., 2025).

Finally, human physiology and neurochemistry also act as preconditions for learning from mistakes, as well as for individuals' affective responses to making mistakes (Hidi & Renninger, 2019; Margulieux et al., 2023). These propose that making mistakes can trigger conditions necessary for neuroplasticity, which can enable the brain to adapt and grow (Darabi et al., 2018; Margulieux et al., 2023). However, the same neurochemicals can cause frustration; thus, how one psychologically perceives mistakes can impact the effect on motivation (Margulieux et al., 2023). Therefore, goal setting can play a crucial role in using mistakes productively: if the goal of the laboratory course is to learn as much as possible, a momentary deviation from the expected trajectory of the laboratory experiment, that is, a mistake, is not a failure or a major roadblock in the pursuit of understanding (DeKorver & Towns, 2015; Margulieux et al., 2023; Schechtel & Bongers, 2026).

2.4 The present study

This thesis examines students' situational affective responses to mistakes in an undergraduate chemistry laboratory course. The study particularly focuses on students' situational engagement and emotions that unfold across versatile learning situations within the course, including pre-lab activities and different phases of laboratory work. The roles of individual, situational, and contextual factors in shaping these experiences are taken into account, while the study also focuses on how prior experiences can influence students' affect later on.

The thesis contributes to the field of research on the role of mistakes in learning by addressing several previously under-researched aspects. These include the focus on the affective learning domain, particularly at the situational level and in an ecologically valid context of the chemistry laboratory, using a person-in-context approach (Sinatra et al., 2015). In this section, the research gaps that this study addresses are established and relevant perspectives adopted are introduced, and then the aims of the thesis, including the general research questions, are articulated.

2.4.1 The perspectives adopted

Only ten years ago, notably little research had paid attention to students' affective responses to making mistakes (Tulis et al., 2016). After that, a growing body of literature has emerged, focusing on different affective constructs, such as emotions, attitudes, motivation, and beliefs (see e.g. Chouvalova et al., 2024; Corwin et al., 2022; Henry et al., 2019; Käfer et al., 2019; Leighton et al., 2018; Narciss & Alemdag, 2025; Nunes et al., 2022; Reindl et al., 2020; Steuer et al., 2025; Tulis et al., 2018). In general, these previous studies indicate that students experience a significant fear of failure in STEM learning contexts, often leading to anxiety and frustration when they make mistakes; however, environmental and individual factors can influence these beliefs and responses. For example, in a mistake-friendly environment, students are more inclined to react positively to mistakes, and the same applies to individuals who adopt a mastery goal orientation. Still, additional research is required to consider a broader range of affective experiences in responses to mistakes, particularly at the situational level and with due respect to the individual and situational conditions (Narciss & Alemdag, 2025; Tulis & Dresel, 2025).

Indeed, previous research suggests that mistakes are very contextual and should be studied in authentic, ecologically valid settings rather than highly controlled experimental settings (Frese & Keith, 2015; Narciss & Alemdag, 2025; Schechtel & Bongers, 2026; Schmid et al., 2025). Regardless, there is still minimal empirical knowledge about students' in-situ responses to mistakes. Thereby, investigating mistakes through an ecological momentary assessment design, capturing them through a situational lens in an authentic setting, is of high value and contributes to the current body of research with its novel approach (Schmid et al., 2025). Furthermore, in the field of chemistry laboratory research, this topic has remained practically untouched until a very recent study on students' affective responses to *failure* (Schechtel & Bongers, 2026), which, still, fundamentally differs from the focus on mistakes and approaches the phenomenon with qualitative measures.

Therefore, in this thesis, these perspectives are adopted, and students' experiences of mistakes are investigated in a chemistry laboratory course through situational measures collected in an ecologically valid context. The thesis integrates several lines of research, and it builds on the research of, for example, Tulis and colleagues (2011; 2016; 2018) on the role of mistakes in learning (*educational psychology*), Galloway and colleagues (2016) as well as DeKorver and Towns (2015) on affective learning in the laboratory (*chemistry education*), and Inkinen and colleagues (2019; 2020) on the research design (*science education*). Mistakes are approached as situation-specific instances that dynamically impact students' affect, including their emotions and situational engagement. Essentially, when this thesis refers to 'making mistakes', it addresses students' subjective experiences of encountering mistakes in Studies I and II, while more objective performance-based mistakes in Study III.

This method is ideal for approaching the phenomenon from the cognitive-motivational learning framework that also considers the sociocultural context, which was adopted in this study and introduced at the beginning of this chapter (see Pekrun, 2024). This methodology follows a person-in-context perspective, positioning the students as individuals within the context of a chemistry laboratory course, dynamic in time (Sinatra et al., 2015). Consequently, this also allows for considering individual conditions, as previous research has suggested they matter in shaping students' affective reactions to mistakes, yet there is still relatively little research on *how* (Agustian et al., 2025b; Narciss & Alemdag, 2025). In this thesis, individual factors including gender, academic performance, study major, and motivational factors are considered, as they have been associated with students' affective experiences previously (e.g. Eccles & Wigfield, 2020; Pekrun, 2006; Pelch, 2018).

Finally, prior research has suggested that students' affective processes following mistakes are related to the specific mistake situation (Corwin et al., 2022; Henry et al., 2019; Sharabi & Roth, 2025; Tulis et al., 2016, 2018). Therefore, in addition to the individual conditions, contextual and situational conditions are also taken into consideration in the sub-studies comprising this thesis (Narciss & Alemdag, 2025; Pekrun, 2024). Based on previous studies, mistake-situation factors, including the type of mistake (Allchin, 2012), the cause of the mistake (Frese & Keith, 2015), and the form of support received in solving the mistake (Keen & Sevian, 2022), are established as situational determinants. To account for the context, the topic of the experiment (Pekrun, 2006), as well as the phase of the experiment and the course (Atabek-Yigit & Senoz, 2023a), are considered to be antecedents of students' affective experiences.

2.4.2 The aims of the thesis

It is known that students tend to make mistakes during chemistry laboratory work; yet, to this date, their affective reactions to these mistakes have remained significantly underexplored (Agustian et al., 2025b; Schechtel & Bongers, 2026). To address this research gap, the main aim of this thesis is to provide insights into students' affective responses to mistakes in an undergraduate-level chemistry laboratory course. To foster a more comprehensive understanding of the phenomenon, various factors that may theoretically influence students' affective experiences and reactions to mistakes are examined. As was described in the subsection above, these factors encompass individual, mistake-situation, and contextual ones. Their relationship to the investigated phenomenon is presented in a conceptual model in Figure 3. Furthermore, although it is not a central focus of the thesis, the roles of individual and contextual factors in predicting the likelihood of making mistakes (represented by the dotted lines in Figure 3) are included as controls.

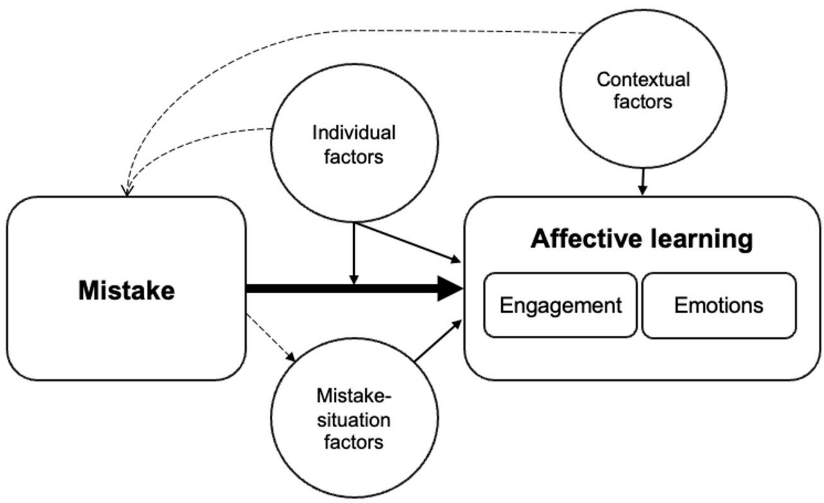

Figure 3. Conceptual model of the main aims of this research. The dotted lines represent associations that are controlled for but not the central focus of this thesis.

Accordingly, three general research questions were formulated. The general research questions are as follows:

1. To what extent does making mistakes impact students' affective experiences in a chemistry laboratory course? (Studies I, II, and III)
2. To what extent do individual factors (i.e., performance, gender, major, motivational factors), mistake-situation factors (i.e., receiving support, type and cause of mistake), and contextual factors (i.e., pre-lab activity/laboratory session, practical phase, theory and practice integration -phase, topic of the experiment), mediate, moderate, or directly impact these experiences? (Studies I, II, and III)
3. To what extent do making mistakes and affective experiences during pre-lab activities predict students' affective experiences in the following laboratory session? (Study III)

All three sub-studies (I, II, and III) address the first research question with different focuses: Study I investigates how mistakes impact students' situational engagement in the lab; Study II examines how mistakes impact students' emotions in the lab; and Study III explores how making mistakes impacts students' situational engagement in online pre-lab activities. All of them also address the second research question: Study I considers all individual, mistake-situation, and contextual factors, Study II examines the roles of individual and mistake-situation factors, whereas Study III focuses on contextual factors. Finally, Study III further addresses the third research question, looking into how mistakes and situational engagement during online pre-lab activities predict students' situational engagement in the subsequent laboratory session.

Beyond answering these research questions, other multidimensional objectives were formulated along the research project. While these objectives also inform the general research questions posed in this dissertation, they primarily emerged from the previous body of literature (as presented earlier in this chapter) during the research process of the individual sub-studies. As such, these objectives were not explicitly used in the formulation of specific aspects of the research design, such as the data collection, which will be presented in Chapter 3. These objectives encompass theoretical, methodological, and practical aims, and they are presented in more detail below:

- **Theoretical aims:** To contribute to the ongoing discourses of 1) the role of mistakes in learning (see e.g. Narciss & Alemdag, 2025; Steuer et al., 2025), and 2) students' affective learning in chemistry laboratory courses (see e.g. Agustian et al., 2022; Seery et al., 2019).

- **Methodological aims:** To contribute to the body of research on the role of mistakes in learning by approaching them on task and in situ (Narciss & Alemdag, 2025; Tulis & Dresel, 2025). To model students' intra- and interindividual variance of in-situ affective experiences using advanced statistical methods.
- **Practical aims:** To contribute to the reform of chemistry laboratory education (see also e.g. DeKorver & Towns, 2015; Keen & Sevian, 2022; Seery et al., 2024), to provide educators with new insights on how to support students' learning in chemistry laboratory courses, particularly in situations involving mistakes (see also Agustian et al., 2025b; Keen & Sevian, 2022), and to gain perceptions on how these matters should be addressed in teacher education (see also Lutovac, 2019; Simpson et al,. 2025).

3 Methods

This chapter begins with an overview of the methodology, presented in Table 3. After that, the context, participants, data collection, different measures, data analyses and ethical considerations are presented in more detail. Finally, the chapter concludes with a disclosure for the ethical use of AI in this thesis.

The data for this study were collected from an undergraduate chemistry laboratory course in 2023 and 2024. The research in each sub-study represents a quantitative approach. In this chapter, frameworks for the data analyses and statistical models are summarized only briefly, and they are described in more detail in the original publications.

3.1 Overview of the methodology

Table 3. A methodological overview of all three sub-studies, including the main aims, participants, variables, data collection, and data analyses.

	Study I	Study II	Study III
Main aim	To examine how making mistakes impacts students' situational engagement in the laboratory	To examine how making mistakes impacts students' emotions in the laboratory	To examine how making mistakes and SE during pre-lab activities impact students' SE in the subsequent laboratory sessions
Participants	University students participating in the first undergraduate chemistry laboratory course		
	2023 (N=155)	2023 and 2024 (N=240)	2023 and 2024 (N=256)
Variables	Situational engagement (interest, skill, and challenge) Mistakes and mistake-situation factors (type of mistake, form of support) Individual factors (gender, performance, major) Contextual factors (phases of work integrating theory and practice, experiment)	Activity-related emotions (excitement, relaxation, frustration, anxiety, and boredom) Mistakes and mistake-situation factors (cause of mistake, form of support) Individual factors (gender, performance, motivational factors)	Situational engagement (interest, skill, and challenge) Pre-lab exercise points indicating mistakes in pre-labs Contextual factors (progress across the course, progress within the session, experiment)
Data collection	Background questionnaire Pre-lab exercise points Ecological momentary assessment questionnaires during laboratory sessions (studies I, II, and III) and pre-labs (study III)		
Data analyses	Multilevel (2-level) structural equation modeling with random intercepts and regression analyses	Multilevel (2-level) structural equation modeling with random intercepts and with random slopes	(Longitudinal) multilevel (2- and 3-level) structural equation modeling with random intercepts, resembling cross-lagged panel models

3.2 Context

All three studies were conducted in the first undergraduate chemistry laboratory course in a Finnish university. The primary learning objectives of the laboratory course were to 'learn to do science' (Hodson, 2014), particularly to be able to safely perform standard laboratory experiments under instruction and to master some basic separation and analysis methods. Additionally, the objectives included the 'learn about science' perspective, as students were expected to introduce themselves with the epistemology of science and chemistry by participating in its epistemic work, as well as to 'learn science', as students ought to be able to understand the contents of the experiments (Hodson, 2014). At the beginning of the course, students participated in a lecture about laboratory safety, followed by an electronic quiz on safety matters they had to pass before entering the laboratory. There were seven practical experiments in the course, covering different topics and traditional undergraduate laboratory tasks: 1. Preparing standard solutions and measuring concentration, 2. Finding the equilibrium constant spectrophotometrically, 3. Distillation, 4. Liquid–liquid extraction, 5. pH-titration, 6. Complexometric titration, and 7. Buffer solutions. The experiments were recipe-style, low in the level of open inquiry (Buck et al., 2008).

Before the laboratory experiments, students were asked to complete preparative learning exercises, 'pre-labs', on an online learning platform. The pre-labs were to be completed before entering the laboratory, but no more than one week in advance. The pre-labs were related to the topic of the subsequent laboratory experiment, and thus, embedded in the overall laboratory learning process (Agustian & Seery, 2017). They consisted of studying the laboratory manual for the upcoming experiment and then completing, for example, questions about the key methods and procedures, simulations, and calculations. Completing the pre-lab tasks was designed to take approximately an hour each week. After responding to a brief questionnaire and submitting their responses, the students received automatic feedback indicating which tasks they had completed correctly or partially correctly. Thus, the feedback revealed whether they had made mistakes in the pre-labs or not.

The weekly laboratory sessions spanned 7 weeks. They were carried out in teaching laboratories with one teacher per 16-student group, and although there were several teachers, each group was led by the same teacher every week. There were no teaching assistants. The 3 to 4-hour experiments were conducted in pairs, with the same pair each week. The students were expected to keep a laboratory diary, and once they finished the experiment, they presented it to the teacher and discussed their work. There were three alternative yet predetermined orders in which students performed the experiments: 1, 2, 3, 5, 7, 4, 6 or 1, 3, 2, 4, 6, 5, 7 or 1, 2, 5, 3, 4, 6, 7. This was due to the practical arrangements of the course, but it also decreased the noise in the data caused by how students progressed along the course.

3.3 Participants

All students who participated in the laboratory course described above in the fall semesters of 2023 and 2024 were invited to participate in the research. In 2023, 178 students enrolled in the course, and 155 (87.1 %) of them participated in the research; in 2024, 142 students enrolled in the course, and 101 (71.1 %) of them participated in the research. Thus, in total, 256 students took part in the study.

The demographics of the participants, including their gender identity, study years, and study major, are presented in Table 4. In 2023, the course was mandatory for chemistry, biochemistry, and biotechnology majors as well as chemistry minors. However, in 2024, due to the new curriculum period at the university, a separate course was organized for chemistry majors, and this course remained mandatory for biochemistry, biotechnology majors and chemistry minors, and became mandatory for food technology majors. Thus, this shift is reflected in the participants' study majors between these two years.

Table 4. The demographics of the participants, including gender identity, study year, and study major.

	In total (n=256)		2023 (n=155)		2024 (n=101)	
	n	%	n	%	n	%
Gender identity						
Female	185	72.3	115	74.2	70	69.3
Male	65	25.4	36	23.2	29	28.7
Other	6	2.3	4	2.6	2	2.0
Study year						
1st	188	73.4	124	80.0	64	63.4
2nd	33	12.9	18	11.3	15	14.9
3rd or above	35	13.7	13	8.4	22	21.8
Study major						
Biochemistry	78	30.9	43	27.7	35	34.7
Biotechnology	62	24.2	35	22.6	27	26.7
Chemistry	47	18.4	47	30.3	0	0.0
Physics	20	7.8	8	5.2	12	11.9
Biology	11	4.3	7	4.5	4	4.0
Mathematics	8	3.1	6	3.9	2	2.0
Geology	8	3.1	0	0.0	8	7.9
Material technology	6	2.3	4	2.6	2	2.0
Food technology	6	2.3	0	0	6	5.9
Other subjects	10	3.9	5	3.2	5	5.0

3.4 Data collection

The research data used in all three studies comprising this thesis were collected from the laboratory courses described above in the fall semesters of 2023 and 2024. In both years, the data collection followed an identical structure, spanning the entire course. The research data were collected from three types of sources, including a background questionnaire, ecological momentary assessment (EMA) questionnaires, and the pre-lab exercises. Their roles in data collection are described below, source by source.

First, the participants responded to a background questionnaire at the beginning of the laboratory course. In the background questionnaires, they gave consent for their participation, and reported the demographics described in section '3.2 Participants'. The background questionnaire also included items measuring students' motivation. All measures are described in full detail below in their own section, '3.4 Measures'.

Second, the predominant data collection tool – used for capturing students' situational engagement and emotions – in each of the three studies was the EMA questionnaires. In an EMA design brief, repeated questionnaires are administered to collect self-reports concerning individuals' momentary experiences at fixed measurement points over a given time period (Kitterød & Lyngstad, 2005). As in the EMA design, participants reflect on their experiences in authentic and ecologically valid settings, the data obtained is of a highly situational and contextual nature with minimal recall bias (Hektner et al., 2007; Kitterød & Lyngstad, 2005).

In this study, a total of 20 ESM questionnaires were administered on an online learning platform used in the course. Seven of the questionnaires were conducted after the pre-lab activities, and the remainder were administered in four laboratory sessions. The questionnaires linked to the pre-labs automatically appeared after students had completed the tasks, yet before they received any feedback. During the laboratory sessions, students were asked to respond to the EMA questionnaires at predetermined points, after completing a specific section of the experiment; the links to these EMA questionnaires were embedded in the work instructions. These four laboratory sessions, in which the data were collected, spanned the following experiments: 4. Liquid–liquid extraction, 5. pH-titration, 6. Complexometric titration, and 7. Buffer solutions. Regardless of the alternative orders in which the experiments could be performed, all students had completed the first experiment (1. Preparing standard solutions and measuring concentration) before data collection in the laboratory began. Thus, they were familiar with the standard practices and chemical equipment used in the laboratory. Altogether, the EMA questionnaires resulted in N=3,354 situational responses. Again, the measures used in the EMA questionnaires are described in their own section, 3.4.

It is important to note that, particularly during the laboratory sessions, students had to pay attention to multiple things even without the data collection. As a result, they may not have responded to all EMA questionnaires, resulting in a relatively low (48%) compliance rate. In pre-labs, the compliance rate was significantly higher (98 %), as the questionnaires appeared automatically after completing the tasks.

As a third data collection source, students' exercise points from the pre-labs were also utilized for research purposes. The exercises were automatically assessed, giving out a total score and indicating which subtasks students had responded correctly or partially correctly to. This information was used to comprise a 'performance' variable (in Study I and Study II) and to detect students' mistakes in the pre-labs (Study III). These are, again, presented in more detail in section 3.4.

For Study I, only the data collected in the fall semester of 2023 were used. Studies II and III, on the other hand, combine and employ the research data collected in both years. Nevertheless, all three studies harness each one of the data sources (background questionnaire, EMAs and pre-lab exercise points) in some way, described in more detail in the original publications.

3.5 Measures

All questionnaires used in the three studies of this thesis were implemented in Finnish, and the phrasing of the items was aligned with previous research. The detailed items and scales for situational engagement, emotions, mistakes, and background variables are described below, respectively.

3.5.1 Situational engagement

Students' situational engagement in the pre-labs and the laboratory sessions was measured with the EMA questionnaires. The situational engagement measures were introduced with the following sentence: "The following questions are related to the [pre-lab activity] / [phase of the laboratory experiment] that you were just working on." As students' situational engagement was examined according to Schneider and colleagues' (2016) conceptualization, situational interest, perceived skill, and task difficulty were measured with the following items, aligning with ones used in previous research (Inkinen et al., 2019, 2020; B. Schneider et al., 2016; Tang et al., 2025): "Were you interested in what you were doing?", "Did you feel skilled at what you were doing?", and "Did you feel challenged by what you were doing?". They were asked to report their level of agreement on a 5-point Likert scale with response categories ranging from "1=Not at all" to "5=Very much".

OLMs were coded in the data based on the measures of the three elements. If an individual simultaneously evaluated the levels of all three variables above the average of the population, an OLM was present, and in all other cases, it was not. Situational engagement measures from the lab sessions were utilized in Studies I and III, combined with those from the pre-lab activities in Study III.

3.5.2 Emotions

Students' situational emotions were also measured with the EMA questionnaires. The activity-related academic emotions, examined in Study II, were measured based on a larger emotion scale used in previous studies (e.g. Vilhunen et al., 2021; 2022), originally modified from Pekrun and colleagues' (2017) Epistemically-Related Emotions Scale. In the EMA questionnaires, after the situational engagement items, students were introduced to the activity-related emotion items with: “How well do the following words describe your feelings during the previous activity? I was…”. Then, they reported the levels of their emotions, “Excited”, “Relaxed”, “Frustrated”, “Anxious”, and “Bored”, on a 5-point Likert scale with response categories ranging from “1=Not at all” to “5=Very much”. These items cover the four quadrants of the two-dimensional emotional map (see Russell, 1980), with frustration reflecting more retrospective and anxiety a more prospective negative activating emotion (Pekrun, 2024). These exact emotions were selected for Study II, as they tend to represent the associated valence and arousal rather consistently: excitement and relaxation are strongly associated with physiological processes reflecting a positive valence and high/low arousal (Ketonen et al., 2023), anxiety and frustration are consistently categorized into negative valence and high arousal (e.g. Flückiger et al., 2025; Pekrun et al., 2018), yet boredom seems to relate to varying strengths of negativity but consistently relatively low arousal (Goetz et al., 2014).

3.5.3 Mistakes

In the pre-lab activities, students' mistakes were detected based on their exercise points. If the student did not receive the maximum points for a subtask, it was assumed that they had made a mistake. Therefore, pre-lab responses that diverged from the maximum of 21 points were coded as pre-lab mistakes and, thus, were rather objective. The most common mistakes included errors in calculations or misunderstandings of the laboratory instructions for the upcoming experiment; however, these mistakes were not categorised separately. These were the focus of Study III.

In the laboratory, for Studies I and II, students self-reported their mistakes in the EMA questionnaires, reflecting their subjective experiences. The identification and, accordingly, the definition of a mistake was left for the students, as presumably, they emotionally respond to their perception of a mistake. They were asked, “Did you notice making a mistake?", with response categories "Yes" and "No". This item was used to construct a binary mistake variable for Studies I and II. Furthermore, if the student responded yes, they were instructed to select all applicable claims. These claims included: "The mistake regarded practical working" (named as *Mistake, experimental*), "The mistake regarded interpreting results or doing calculations" (i.e., *Mistake, conceptual*), "Teacher helped me solve the mistake" (i.e., *Mistake, teacher helped*), "Peers helped me solve the mistake" (i.e., *Mistake, peers helped*), "The mistake was caused by my carelessness" (i.e., *Mistake, careless*), "The mistake was caused by the lack of my skills or knowledge" (i.e., *Mistake, lack of skill*), and "The reason behind the mistake remained unclear" (i.e., *Mistake, unclear*).

These claims, reflecting mistake-situation factors, were used to form subcategories of mistakes, which were used in Studies I and II. These subcategories of mistakes were based on notions of the types and causes of mistakes in previous studies (Allchin, 2012; Frese & Keith, 2015; Reason, 1990; Simpson et al., 2020), and different forms of support have been identified as an important antecedent of students' mistake experiences (Keen & Sevian, 2022; Leighton et al., 2018; Soncini et al., 2022; Tulis, 2013; Wan et al., 2023). The number of mistakes in each category is presented in Table 5. As several claims could apply to one mistake, these categories were not mutually exclusive. However, as there were so few mistakes (n=18) within the category *Mistake, unclear*, this category was not included in any of the three sub-studies.

Table 5. The number of mistakes in each mistake category in 2023, 2024, and in total.

	N (2023)	N (2024)	N (in total)
Mistake	304	162	466
Experimental	127	75	202
Conceptual	132	70	202
Careless	139	62	201
Lack of skill	59	9	68
Teacher helped	93	43	136
Peers helped	67	31	98
Unclear	15	3	18

3.5.4 Background variables

In the background questionnaire, students' demographics, including their gender identity, study years, and major subject, were collected. Another individual-level variable, namely students' performance levels in the course, was determined by comparing their total score of all pre-lab activities against the maximum score (see

Studies I and II for details). In addition to these, the background questionnaire contained items on students' motivational factors. A modified, chemistry-laboratory-specific questionnaire, adapted from Ronkainen and colleagues' (2024) questionnaire within the expectancy value theory framework (Eccles et al., 1983), was used for this purpose. The questionnaire consisted of a larger number of items, but in this thesis, students' perceptions of the utility of the laboratory activities, as well as their perceived emotional costs of the laboratory activities, were focused on. Utility value was measured with two items: "It is useful for me to do the practical work in chemistry" and "During practical work in chemistry, I learn skills that are important for my career", and cost value also with two items: "Doing practical work in chemistry exhausts me", and "Doing practical work in chemistry stresses me". Students responded on a 5-point Likert scale, with response categories ranging from "1=Totally disagree" to "5=Totally agree". The items were used as indicators of latent factors, utility value and cost value, which were used as individual-level covariates in Study II.

3.6 Data analyses

All three sub-studies comprising this thesis are based on quantitative data, examined through statistical analyses, precisely within a multilevel structural equation modeling (MSEM) framework. Mplus software versions 8.6–8.11 (Muthén & Muthén, 1998–2017) were used to conduct all analyses, which are described in greater detail in the original publications. The selection of this approach, as well as the key differences between the modeling approaches used in the sub-studies, are distinguished in this section. These include regression analyses, MSEM with random intercepts, MSEM with random slopes, and cross-lagged panel models.

Overall, the MSEM framework was selected, as the data is hierarchically structured. The predominant data collection design, EMA, provides repeated measures of the examined variables (e.g. situational engagement) from individuals. Thereby, there are up to 20 situational measures per student, meaning that the situational responses are nested within individuals. This is important, as within-student responses may have higher similarity than the responses between students, and multilevel frameworks account for this situational (also referred to as within-level or level 1) vs. individual (i.e., between-level or level 2) level variability. This two-level structure was considered in Studies I and II. Nevertheless, the data can also be structured within a three-level hierarchy, where situations (level 1) are nested within lessons (level 2), which are in turn nested within individuals (level 3). This three-level structure was applied in Study III.

The multilevel approaches used in all studies were supported by high intraclass correlation coefficients (ICCs) of the variables, indicating that a significant proportion of the variance is distributed across both (or all three) levels. A multilevel approach is suggested when the ICCs are above .10 (Irimata & Wilson, 2018), which was true for situational engagement, its elements, emotions, and making mistakes. However, according to the ICC values, the variance of the mistake variable was mostly distributed across the situational level, as only 10 % of the variance was explained by the individual level. For the affective constructs, the variances were more evenly distributed across the levels, with 19–42% of the variance explained by the individual level.

The simplest statistical approaches used in the sub-studies are regression analyses that focus on the simple relationship between independent (predictor) and dependent (outcome) variables. In Study I, due to the relatively small number of observations in each mistake category, the relationships between dummy-coded mistake categories (predictors) as well as situational engagement and its elements (outcomes) were modelled only at the situational level using logistic and linear regression analyses, respectively.

Although regression models can be specified as multilevel models (MLM), the MSEM framework provides a more subtle approach. It allows for incorporating latent variables as predictors and outcomes, and in addition, more complex causal paths can be modelled (Muthén, 1994). However, the boundaries between these frameworks can sometimes be comparatively fluid, as both rely on the partition of within- and between-level variances, and in cases where only observed variables are examined and no latent variables are specified, they are also mathematically equivalent (Muthén, 1994; Preacher et al., 2010). A common detail distinguishing these as separate frameworks is that in MSEM, the between-level averages are treated as latent variables (Lüdtke et al., 2008; Preacher et al., 2010). Accordingly, the models are no longer mathematically identical, although they may still yield the same parameter estimates and remain statistically equivalent (Muthén, 1994; Lüdtke et al., 2008; Preacher et al., 2010).

For example, in Studies II and III, the associations between students' affective experiences (situational engagement or emotions) and mistakes were investigated using MSEM models, which are statistically equivalent to multilevel regression models, controlling for individual-level variability in affective experiences (i.e., MLM) (Muthén, 1994). Nevertheless, in these models, the between-level averages were treated as latent variables, and thereby they are interpreted within the MSEM with random intercepts framework. In such a framework, independent variables predict the intercepts of the dependent outcomes. This means that they account for the average level of the outcome variable across situations and for systematic variance in the outcome across individuals; for example, the situational level of an emotion (observed) could depend on whether a student has made a mistake, and the trait-like individual level of the emotion (latent) could depend on gender.

Again, a little more subtle approach, MSEM with random slopes, was used as an analytical framework in Study II. In such a model, the independent variables predict the slopes instead of the intercepts (Muthén & Muthén, 1998–2017). In other words, also cross-level associations (i.e., moderation) can be modelled (Hall & Malmberg, 2020). In practice, this means that an independent variable predicts not the level of the latent outcome variable, but how strongly and in what direction another independent variable affects the outcome. For example, in Study II, individual factors, including latent motivation variables, predict the slope of emotions when students make mistakes, reflecting how much the individual factors impact the direction and intensity with which the level of that emotion changes in mistake situations. That is, they moderate the relationship between mistakes and emotions.

A third and final approach expressed within the MSEM framework in this thesis is the time-sensitive cross-lagged panel model. In such a model, so-called lagged effects between the variables across multiple points in time can be modelled to investigate causal reciprocal relationships in longitudinal data (Kearney, 2017). In Study III, three-level MSEM models resembling a cross-lagged panel model were specified. However, these models were not pure cross-lagged panel models, as not all autoregressive and cross-lagged paths were included in the model. Namely, in the models, situational engagement in pre-labs predicted students' situational engagement in all measurement points of the laboratory session, but situational engagement trajectories within the laboratory session were not modelled.

Finally, the analyses were performed with maximum likelihood for robust standard error (MLR) and weighted least square mean and variance adjusted (WLSMV) estimation, which do not rely on normal distributions in the data. MLR is recommended for continuous outcomes, and WLSMV for binary or ordinal outcomes. As the data were missing completely at random (Little's MCAR test, χ^2=116.4, p=0.928), missing data were handled by the Full Information Maximum Likelihood (FIML) method in all sub-studies.

3.7 Ethical considerations

The research met all the ethics requirements for research involving human subjects, and the ethical guidelines of the Finnish National Board of Research Integrity TENK were followed (Finnish National Board on Research Integrity TENK, 2019). Participants were not posed to any risk, nor was the research associated with high physical or emotional stress. All participants were informed about the absolute voluntariness of participation, the study objectives, the protection of data privacy, and the non-risk character of the study, after which they actively gave consent to use their questionnaire responses for research purposes in the background questionnaire.

They were also provided with contact information for questions, problems, or withdrawing their consent.

Participation in the research activities was part of the regular coursework, and it was designed to distract students from the coursework as little as possible. Mistakes were not specifically designed into the course but rather studied as a naturally occurring phenomenon. Accordingly, the implementation of the study did not purposefully cause any additional distress to students.

3.8 Artificial intelligence disclosure

In this thesis, artificial intelligence tools (ChatGPT, GPT-5.1; Grammarly) were used for technical assistance in language editing and generating or correcting the reference list according to APA 7 guidelines. All substantive content and interpretations are the author's own. Similar AI practices were adopted in all three sub-studies.

4 An overview of the original studies

This thesis comprises three individual empirical studies. The research questions and key findings of each study are presented in this chapter, study by study. As described in the Methods chapter, the research data for all three studies were collected from an undergraduate laboratory course in 2023 (n=155) and 2024 (n=101) using an ecological momentary assessment (EMA) design with repeated self-report measurements. Individual-level variables, used in Studies I and II, were reported in a background questionnaire. Study I only employed the data from 2023, whereas Studies II and III used the data from both years. All studies relied on quantitative questionnaire data, which were analyzed using versatile statistical approaches within the MSEM framework. The main findings are summarized in Table 6.

4.1 Study I: How making mistakes shapes students' situational engagement in chemistry laboratory?

The aims of Study I (Kyynäräinen et al., 2024) were to examine how making mistakes impacts students' situational engagement (SE) in the laboratory, controlling for the student-level averages of situational engagement and the probabilities with which students may make mistakes, as well as to investigate what kind of role the mistake-situation factors (i.e., the type of mistake and the form of support) play in shaping students' situational engagement. The data consisted of n=1049 EMA responses from the laboratory.

The specific research questions were as follows:

1. To what extent do gender, major, and performance affect students' probability of making mistakes and their situational engagement?
2. To what extent do combining theory with practice and making mistakes affect students' situational engagement?
3. To what extent do the type of mistake and the form of support used in solving the mistake affect students' situational engagement?

First, as an emergent finding, the study revealed the high frequency of mistake instances during the laboratory experiments (29 %). Based on the results of an MSEM model, students with a higher performance level were less likely to make mistakes. Although a higher performance level was not associated with a higher probability of experiencing OLMs (i.e., high situational engagement), it was related to the levels of all OLM elements, namely higher interest and higher perceived skills, as well as with a perception of lower challenge. Gender and major were not linked to the probability of making mistakes or OLMs at a statistically significant level. In terms of contextual factors, phases of work in which students had to combine theory and practice predicted a higher probability of making mistakes and experiencing OLMs, lower levels of interest and skill, and higher challenge. Thus, the low challenge levels seemed to be the barrier to experiencing OLMs, and although the levels of interest and skill decreased in these phases, they remained high enough to experience OLMs. Students' mistakes, on the other hand, did not directly predict the probability of experiencing OLMs, although they were, as well, associated with lower interest and skill, and higher challenge.

According to a logistic regression model, none of the mistake-situation factors focused on impacted the students' probability of experiencing OLMs. A linear regression model revealed that experimental mistakes were associated with higher levels of interest and skill, and lower levels of challenge, whereas conceptual mistakes were related to the opposite in terms of skill and challenge. Teacher and peer support in solving the mistake were associated with higher levels of challenge, but only teacher support was related to lower perceived skills at a statistically significant level.

To conclude, this study emphasizes the importance of understanding students' situational responses to mistakes in more depth. Mistakes do not seem to disturb students' situational engagement, and they may even have the potential to promote high situational engagement through increasing the challenge. Students' situational engagement could be supported by strengthening the connections between theory and practice and encouraging collaborative ways of solving mistakes.

4.2 Study II: Students' emotional responses to mistakes: An ecological momentary assessment study in university chemistry laboratory

The aims of Study II (Kyynäräinen et al., submitted) were to examine students' in-situ emotional responses to mistakes and which individual factors moderate these responses, as well as how mistake-situation factors (including the cause of the mistake and the form of support) impact the levels of these emotions. The data consisted of n=1635 EMA responses from the laboratory.

The specific research questions were as follows:

1. To what extent does making mistakes impact students' levels of excitement, relaxation, frustration, anxiety, and boredom in the chemistry laboratory?
2. To what extent do the students' gender, performance level, and subjective task values affect and moderate the levels of these emotions during mistake situations in the chemistry laboratory?
3. To what extent does the cause of the mistake or receiving help to solve the mistake affect the levels of these emotions?

An MSEM model reveals that students experience a little lower level of excitement, a significantly lower level of relaxation, and significantly higher levels of anxiety and particularly frustration when they make mistakes. Subjective task values (i.e., utility and cost value of laboratory activities) predicted the levels of emotions during laboratory work in general. Males also experienced higher levels of overall relaxation. These relationships, as well as the roles of these individual factors in moderating the emotional response to mistakes, were studied with an MSEM model with random slopes. The model revealed that high-performing students remained more relaxed and became less anxious and frustrated in mistake situations, whereas students with high perceived cost value experienced a stronger increase in anxiety in mistake situations. The increased anxiety demonstrated by the latter group of students may reflect a fear of prospective failure. Considering the mistake-situation factors, careless mistakes were associated with a higher level of excitement, whereas mistakes caused by lack of skill or knowledge intensified the effects of mistakes in general. Teacher support in solving the mistake related to lower relaxation and higher anxiety and frustration, whereas peer support did not impact the levels of any of the studied emotions at a statistically significant level.

Overall, the results suggest that mistakes can trigger different kinds of situational emotions in students depending on situational or individual factors, and some individual factors can even predict trait-like emotions in mistake situations. The results support the findings of Study I; positioning peer help as more neutral in comparison to frustration- and anxiety-increasing teacher support. This study also reveals that individual factors can play an important role in influencing students' affective responses to mistakes, not just the probability of making mistakes and the levels of the affective constructs themselves, as was found in Study I. To conclude, the findings advocate the need for targeted IER support in mistake situations – particularly for students with a lower performance level and high perceived emotional costs of laboratory work, and especially when the mistake reflects a skill or knowledge gap.

4.3 Study III: Failing forward in chemistry laboratory courses: the impact of engagement and mistakes during pre-lab activities on students' situational engagement

The aims of Study III (Kyynäräinen et al., 2026) were to examine how mistakes in pre-labs impact students' situational engagement on-task and what role they have in predicting students' situational engagement in subsequent laboratory sessions. The EMA data consisted of n=1006 pre-lab and n=1586 laboratory responses.

The specific research questions were as follows:

1. To what extent is making mistakes associated with students' situational engagement in the pre-lab activities?
2. To what extent do students' situational engagement and making mistakes in the pre-lab activities predict their situational engagement during the subsequent laboratory session?
3. How does students' situational engagement change within a laboratory session and across the laboratory course?

A two-level MSEM model reveals that students experience lower levels of perceived skills and higher perceived task difficulty when they make mistakes in the pre-lab activities, that is 64 % of all instances. The lagged effects of mistakes and situational engagement during pre-labs were studied with three-level MSEM models resembling cross-lagged panel models, and they reveal autoregressive effects from OLMs (i.e., high situational engagement) and all three elements of it from pre-labs to subsequent laboratory sessions. In addition, higher perceived skill level and task difficulty in pre-labs also predicted higher interest in the subsequent laboratory session. Although mistakes impacted students' situational engagement during the pre-labs, they did not display lagged effects on students' situational engagement during the subsequent laboratory session. During the laboratory session, students' probability of experiencing OLMs and perceived challenge increased and perceived skills decreased toward the end of the session. Across the laboratory course, students' skill level increased, and the challenge level decreased.

In conclusion, context appears to influence how students react to mistakes. Unlike the laboratory mistakes in Study I, the pre-lab mistakes were not associated with lower interest. In the pre-labs, exercises were conducted individually in an online learning environment, and students may not have always been aware of their mistakes when reporting their affective experiences, whereas in the real-life laboratory, experiments were carried out in pairs, and students knew they had made a mistake. The results reveal that students may emotionally overcome their mistakes in a relatively short time, whereas situational engagement tends to carry over to the laboratory session.

4.4 Overview of the results

Table 6. An overview of the key empirical findings of the sub-studies directly related to mistake experiences.

	Study I	**Study II**	**Study III**
	Laboratory mistakes	Laboratory mistakes	Pre-lab mistakes
Mistakes	Lower interest and perceived skill Higher perceived challenge	Lower levels of positive emotions Higher levels of anxiety and frustration	Lower perceived skill Higher perceived challenge No lagged effects from pre-lab activities to laboratory sessions
Individual factors	Low performers made more mistakes	Low performers experienced an intense increase in anxiety and frustration, and a decrease in relaxation in mistake situations High costs were linked to an intense increase in anxiety in mistake situations	
Situational factors	Experimental mistakes were perceived as neutral Conceptual mistakes intensified the effects on skill and challenge Teacher support was linked to an intensified decrease in skill and an increase in challenge Peer support intensified the effect on challenge	Careless mistakes were associated with higher positive emotions, and lower anxiety and frustration Mistakes caused by skill or knowledge gaps were linked to an intensified decrease in positive emotions and an increase in anxiety and frustration Teacher support was linked to an intensified decrease in relaxation, and an increase in anxiety and frustration	
Contextual factors	The topic of the experiment affected students' probability of making mistakes Students made more mistakes and experienced higher SE in phases of work where they were to integrate theory and practice		The topic of the pre-lab activity affected students' probability of making mistakes Pre-lab mistakes seem to differ from laboratory mistakes (cf. Study I)

5 Discussion

This chapter focuses on discussing the key findings of the three sub-studies. First, the main findings are addressed, followed by theoretical reflections on these findings. Then, methodological reflections are presented, followed by practical implications. Finally, at the end of this chapter, the limitations of the research are discussed, and some directions for future research are proposed. The research presented in this thesis followed a cognitive-motivational research tradition, taking strong influences especially from Pekrun's CVT (2006, 2024), Eccles and Wigfield's SEVT (2020), as well as Schneider and colleagues' theory of OLMs (2016, 2025). Accordingly, the findings of this thesis are interpreted and discussed within this framework.

5.1 Main findings

Although it was not explicitly addressed in the research questions, one of the major contributions of this thesis can be attributed to the emergent finding of identifying the high frequencies of mistakes that occur during learning in the chemistry laboratory and in the pre-lab activities. Although previous research has suggested that mistakes lie in the essence of the nature of science and thus, laboratory work (Allchin, 2012, 2020; Firestein, 2016; Kipnis, 2011; Nunes et al., 2022; Simpson & Maltese, 2017), to the best of our knowledge, no such explicit examples of how routinely they can indeed occur have been provided. As the results show, students reported that they had made a mistake in almost one-third of all measured learning situations in the laboratory. In the context of the pre-lab activities, students' mistakes were identified based on their exercise points, and they occurred even more frequently: in almost two-thirds of all measured learning situations. These emergent findings – particularly when combined with the prior finding of DeKorver and Towns (2015), stating that students name trying to avoid mistakes as an important goal of chemistry laboratory education – highlight the crucial importance of understanding the role of mistakes across versatile learning situations, which is relevant to this thesis and extends beyond it.

In this section, the main findings of this thesis are discussed based on the conceptual model of this research (see Figure 3 for reference). The first subsection will focus on the findings regarding what the three sub-studies reveal about students' in-situ affective responses to making mistakes in general. Then, the phenomenon is approached one type of factor at a time, shedding light on the roles that individual, mistake-situation, and contextual factors play in shaping students' affective responses to mistakes.

5.1.1 Students' in-situ affective responses to mistakes

As stated in the previous literature, there is very limited prior knowledge about students' situational affective responses to mistakes in general, and specifically in the chemistry laboratory context (Keen, 2021; Schechtel & Bongers, 2026; Schmid et al., 2025; Soncini et al., 2025). Nonetheless, it is known that mistakes are highly contextual and situational, and thereby, it is of high value to understand students' in-situ responses in addition to their broader perspectives on mistakes, failure, or setbacks (Schechtel & Bongers, 2026; Schmid et al., 2025; Soncini et al., 2025). Thus, all three sub-studies of this thesis have a specific focus on students' in-situ affective responses to making mistakes. Study II touched upon students' emotional reactions to making mistakes in the laboratory. Study I approached this topic from the situational engagement point of view, focusing on how making mistakes shaped students' situational engagement in the laboratory. Study III was also focused on situational engagement, but it was situated within the pre-lab activity context.

The findings of Study II suggest that mistakes impact students' emotional levels. In detail, mistake situations are associated with significantly higher levels of anxiety and particularly frustration, as well as significantly lower levels of relaxation and moderately lower levels of excitement. The findings concerning the shifts in the levels of anxiety, frustration, and relaxation are expected, as the relationship between making mistakes and experiencing anxiety and frustration is widely supported by previous studies (Agustian et al., 2025b; Frese & Keith, 2015; Schechtel & Bongers, 2026; Simpson & Maltese, 2017), and an opposite impact can be expected for relaxation as it is situated at the opposite side of the two-dimensional emotional map (Russell, 1980). Nevertheless, this study contributes to the previous body of research by being among the first ones to approach students' emotional responses to mistakes in situ, framing them as state emotions in mistake situations (Pekrun et al., 2018; Schmid et al., 2025). Hence, these findings propose that students may generally experience elevated levels of both negative and activating state emotions when they make mistakes.

Prior research has identified a decrease in students' motivation in response to mistakes based on students' recall of mistake situations (Tulis et al., 2016). Although engagement and motivation are not equivalent, situational engagement could be understood as a proxy for situational motivation, as it reflects a psychological state characterized by deep concentration and positive affect toward ongoing activities (B. Schneider et al., 2016). As such, the findings of Studies I and III do not align with the previous findings of Tulis and colleagues (2016), because they suggest that making mistakes may not be linked to students' probability of experiencing OLMs (i.e., high situational engagement) and thus, it may not be demotivating. Still, it should be noted that they do impact the levels of the OLM elements. In detail, students experienced lower levels of perceived skills and higher levels of perceived challenges in situations when they had made mistakes. Again, these findings can be considered fairly expected as the relationship between students' mistakes and compromised self-efficacy has been discussed in the previous literature (Corwin et al., 2022; Henry et al., 2019; Schmid et al., 2022), and mistakes are sometimes framed as a part of a broader concept of struggles, indicating greater difficulties (Keen & Sevian, 2022). In the light of Pekrun's CVT (2024), these findings are also well-aligned with the theoretical underlying appraisals of control and value in these situations, as students experienced more negative activating emotions, which are linked to low to moderate control and high value, reflecting a temporal overchallenge. Depending on the context (pre-lab task versus laboratory task), students may also have experienced lower levels of interest in such situations, but this is discussed in more detail in subsection entitled '5.1.4 The role of contextual factors'.

The findings of Study III also suggest that although students undergo relatively strong affective responses to mistakes in the present situations, the impacts of mistakes may not carry over to later instances. This is supported by the finding that students' mistakes in the pre-labs were not reflected in either their probability of experiencing OLMs or in their levels of any OLM elements in the subsequent laboratory sessions, emphasizing the situational, short-term nature of the affective responses (Schmid et al., 2025; Soncini et al., 2025). Indeed, the duration of the affective response may be relatively short, which is consistent with previous findings, stating that people are prone to overestimating the duration of emotional responses to setbacks or challenges (Wilson & Gilbert, 2005).

Overall, being characterized as momentary departures from the expected trajectories of the activities, mistakes suddenly bring students control beyond performing the predetermined steps of the experiment within the laboratory context (Galloway et al., 2016; Simpson et al., 2025). In line with the findings, this could account for the increase in students' activating emotions and perceptions of increased challenges (Galloway et al., 2016). This may even promote further learning, as higher emotional activation or agency could alleviate students' negative emotions and emotional responses to mistakes (Corwin et al., 2022; Pekrun, 2006), and as the low challenge level has often been identified as the barrier to experiencing high situational engagement in the chemistry laboratory context (Atabek-Yigit & Senoz, 2023a; Inkinen et al., 2019). Nevertheless, if students' self-concept becomes or remains highly threatened and their emotional schemes too negative, learning will be compromised (Pekrun, 2006; Schechtel & Bongers, 2026; Vilhunen et al., 2023).

To conclude, students' emotional schemes are prone to shifting in a negative direction when they make mistakes in the chemistry laboratory course. However, there is variation across situations, and the results give tentative indications that under some circumstances, mistakes could even foster learning engagement and emotional activation. As such, they could have the potential to promote meaningful learning.

5.1.2 The role of individual factors

Prior research suggests that individual factors can play a significant role in predicting not only students' affective experiences, but also their adaptive coping with mistakes (Henry et al., 2019; Tulis et al., 2016, 2018; Tulis & Fulmer, 2013). These individual differences in students' reactions to mistakes have also been identified in the chemistry laboratory context, yet it is still unclear which factors may indeed impact and how (Agustian et al., 2025b). This research gap is addressed primarily in Study II, which examines how individual factors directly affect students' emotional levels and how they moderate students' affective responses to mistakes. In addition, Study I touches upon the matter by shedding light on how individual factors directly impact students' situational engagement and also their probability of making mistakes. Both sub-studies incorporate gender and performance level as individual factors, while Study I also considers study major, and Study II addresses motivational traits (STVs), including utility value and emotional costs. Understanding the role of individual factors in shaping both the affective experiences and affective responses to mistakes is relevant because the general levels of students' affect set a baseline against which their responses to mistakes can be compared.

First, the findings of Study I suggest that well-performing students were less likely to make mistakes in the laboratory. As the performance level was determined based on the pre-lab exercise points, this might be anticipated, because higher prior knowledge is well known to be associated with better performance (M. Schneider & Preckel, 2017). In a broader context, this is not self-evident, as prior research states that momentarily unoptimized performance, indicated by, for example, mistakes, could sometimes even lead to enhanced learning (Loibl & Leuders, 2019; Soderstrom & Bjork, 2013). A higher performance level was also associated with higher interest and perceived skills, as well as lower perceived challenges. Neither of the other individual factors that were focused on in this sub-study (gender and major) was associated with the probability of making mistakes or the elements of OLMs. Additionally, none of the three individual factors (gender, major, and performance level) was linked to the probability of experiencing OLMs. These results align with previous findings, suggesting that regardless of the students' background, they may be able to deeply engage with the learning situation (Pöysä et al., 2020; B. Schneider et al., 2016).

Second, Study II addressed the phenomenon from the emotional point of view. The findings reveal that the STVs, utility value and emotional costs were associated with students' levels of trait-like emotions in general. High perceived utility value was associated with higher levels of positive emotions and lower levels of negative emotions. In comparison, high perceived emotional costs were associated with lower levels of relaxation and higher levels of anxiety and frustration. There is a deficiency of prior research addressing how these STVs impact the levels of students' emotions in the chemistry laboratory context; however, the findings of this study align with the results from the educational psychology field (Berweger et al., 2022). The results also pointed out that males experienced higher levels of trait-like relaxation. This brings new perspectives into understanding gender differences in emotional levels during laboratory learning, as prior research suggests that females are prone to experiencing higher trait anxiety in scientific disciplines (Cooper et al., 2023; Pelch, 2018; Rummey et al., 2019). Our results do not support this, suggesting that the differences may instead be explained by differences in relaxation levels, given that anxiety is situated on the opposite side of the two-dimensional emotional map (Russell, 1980).

In addition to these direct effects on students' affective experiences, individual factors were also treated as moderators for the emotional responses to mistakes. This approach was selected, as previous research suggests that individual factors, such as stable motivational beliefs or dispositions, may impact students' adaptive reactions to mistakes (Henry et al., 2019; Tulis et al., 2016, 2018). In line, the results of Study II propose that individual factors could indeed impact the directions and intensities of students' emotional reactions to mistakes. In detail, cost value positively moderated the relationship between making mistakes and anxiety, stating that students with higher perceived emotional costs experienced a more intense increase in anxiety as a response to making mistakes. Similar results have also been obtained in previous exploratory work, indicating that undergraduate students with high emotional stress may react exceptionally negatively to mistakes they make in research work (Cooper et al., 2020). It is plausible that these students equate making mistakes with prospective failure, perceiving all unexpected trajectories as inherently negative. Moreover, this finding suggests that more specific STVs may be more strongly linked to students' emotional responses to mistakes in comparison to general subject values (Tulis & Ainley, 2011).

High performance, on the other hand, positively moderated the relationship between making mistakes and relaxation, and negatively moderated the relationship between making mistakes and anxiety, as well as making mistakes and frustration. Thus, high performing students remained more relaxed and became less anxious and frustrated in mistake situations. They may have been able to engage in meta-affective learning through IER and emotional reappraisals, fostering positive affect toward the learning process triggered by their mistakes (Pekrun et al., 2018; Radoff et al., 2019; Sharabi & Roth, 2025). Accordingly, anxiety and frustration may be understood as trait-like emotions in mistake situations for low-performing students, whereas those who obtain high emotional costs experience specifically trait-like anxiety, plausibly reflecting the fear of failure (Pekrun, 2024; Pekrun et al., 2018).

Prior research also suggests that males are more likely to adaptively react to their mistakes (Soncini et al., 2022), which was not observed in these studies. Instead, gender was not associated with the levels of any affective experiences except for the level of relaxation (Studies I and II), nor did it moderate the relationship between making mistakes and emotions (in Study II). As this prior finding is obtained from middle school students in Italy and relates to mathematics learning, such a gender difference may not be present for older students or across different learning contexts. Alternatively, approaching the studied phenomenon in situ can impact; prior research indicates that individual factors may not shape students' dynamic state emotions like they shape their trait-emotions (Goetz et al., 2013; Tulis & Ainley, 2011).

Overall, the results suggest that students' performance level has a strong relationship with their affective experiences and affective responses to mistakes. High-performing students seemed more self-confident, characterized by higher perceived skills and lower perceived challenges, and they also remained more positive when they made mistakes. Perhaps because of their higher self-confidence, they might not feel as threatened by making mistakes and associate it with lower reputational costs (Nunes et al., 2022). On the other hand, the relationship may also be the other way around: more adaptive responses to making mistakes demonstrated by these students could result in deeper learning and thus, higher performance (Huangfu et al., 2023; Soncini et al., 2025; Tulis et al., 2016). Another individual factor of high interest is the perceived emotional costs of laboratory activities. As students who perceive laboratory work as burdensome became intensely anxious in response to mistakes, while they already experienced higher levels of anxiety in the laboratory in general, their emotional schemas may be excessively negative, impairing their learning.

5.1.3 The role of mistake-situation factors

Students' responses to mistakes are highly dependent on the situation (Corwin et al., 2022; Henry et al., 2019; Narciss & Alemdag, 2025; Sharabi & Roth, 2025; Tulis et al., 2016, 2018). Not every mistake – or perhaps not even any two mistakes – are identical (Allchin, 2012; Simpson, 2020). Therefore, it is highly valuable to consider the role of mistake-situation factors, which was done in Studies I and II. In Study I, the type of mistake and the form of support received in solving the mistake were considered as mediators of the shifts in students' situational engagement as a response to mistakes. In turn, Study II considered the cause of the mistake and the form of support received in solving the mistake as mediators of students' emotional responses to mistakes.

Based on the findings of Study I, none of the subcategories of mistakes predicted the probability of experiencing OLMs. However, experimental mistakes were associated with higher levels of interest and significantly higher perceived skill, as well as with a significantly lower level of challenge. In turn, the impacts of conceptual mistakes were the opposite in terms of skill and challenge. In general, experimental phases of laboratory work are associated with higher cognitive demands, which could account for the differences in skill and challenge levels (Galloway & Bretz, 2015; Vilhunen et al., 2021). These differences could also be attributed to the idea that conceptual mistakes may threaten one's self-concept more, whereas experimental mistakes are perceived as more neutral. Experimental mistakes could be less connected to the self and one's own capabilities, and instead, they could be perceived as more external (cf. Allchin, 2012; Henry et al., 2019; Simpson & Maltese, 2017). On the other hand, these types of mistakes are tightly related to the context of the chemistry laboratory or experimental settings in general, which may be less familiar than the classroom settings, where conceptual mistakes can also occur for students (Allchin, 2012; Kipnis, 2011). As such, it could be suggested that students' perceptions of mistakes and coping practices may not transfer to these less-familiar types of mistakes so strongly.

In addition to the type of mistake, the cause was also noted as relevant for students' affective experiences. It was focused on in Study II, which revealed that careless mistakes were associated with higher levels of excitement. In such instances, students were likely more enthusiastic, which could result in higher risk-taking behavior and lower carefulness (Nunes et al., 2022). Mistakes that were caused by the lack of one's skills or knowledge were associated with lower excitement, even lower relaxation, and significantly higher anxiety and frustration. The occurrence of these mistakes reveals that students are challenged beyond their current capabilities. Simply reporting this as the cause of the mistake may indicate that they feel like being faced with tasks that are too challenging for them. This appears to decrease students' levels of positive emotions and significantly increase their anxiety and frustration, which aligns with the prior understanding (Allchin, 2012; Pekrun, 2006; Pekrun et al., 2018). If students arrive at the conclusion that the lack of their expertise is the problem in these situations, instead of something that could be built on and used as a transformative learning experience, it is highly problematic (Schechtel &

Bongers, 2026). Thereby, these mistakes may become a threat to students' learning, particularly if proper instructional activities and affective support are not provided (Keen & Sevian, 2022; Schechtel & Bongers, 2026).

Prior research even suggests that in a context where students feel like they are being judged for their mistakes, they may adopt beliefs of self-blame for any mistake they encounter in the laboratory (Schechtel & Bongers, 2026). What is particularly alarming is that this appeared to protect them against the experience of judgment, as by blaming themselves, they felt recognized by the instructors as belonging in science (Schechtel & Bongers, 2026). This is not at all what is understood about scientific mistakes (Allchin, 2012), and if anything, understanding the nature of science behind and being able to conceptualize and determine the different mistake types should contribute to belonging in science (see also Metcalfe et al., 2025). Importantly, inducing self-blame is not an intended outcome of engaging with mistakes in the context of scientific inquiry. However, arguably, based on Study II, it seems that the students attending this course had not adopted such strong self-blame beliefs, as only a small minority of all mistakes were attributed to the lack of one's skills or knowledge (see Table 5).

Finally, the form of support was focused on in Studies I and II. Study I revealed that the form of support received in solving the mistake impacted students' perceptions of their skill and challenge. Teacher support was associated with a lower level of skill and a higher perception of challenge, whereas peer support was only associated with a higher perceived challenge level. The higher perceived challenge level is likely attributed to students being more likely to seek help when they feel challenged by the mistake. They may also have preferred seeking help from the teachers rather than their peers in instances where they felt less skilled and thus unable to solve the mistake on their own. Alternatively, the teacher's support could have hindered their perceptions of skills. Based on the findings of Study II, teacher support was also linked to experiencing even lower levels of relaxation and higher levels of anxiety and frustration. Similarly, this could result from students being more likely to seek teacher support when they feel more anxious or frustrated and less relaxed, or that teacher support increases their anxiety and frustration, and lowers relaxation. For one, not feeling competent and experiencing negative emotions may result in relying on teacher support as a form of external guidance (Pekrun, 2006). Conversely, the shift towards a more negative emotional landscape could be explained by the sociocultural norms of the laboratory, as students may feel like they are annoying or bugging the teacher with their questions, challenges, and mistakes (Keen & Sevian, 2022; Schechtel & Bongers, 2026), or by the clarity of the assessment practices used, as the students may be afraid that they will be negatively evaluated based on their mistakes (Leighton et al., 2018; Tulis, 2013).

In contrast, being able to resolve mistakes with one's peers may have maintained students' experiences of their capabilities. Indeed, through the theoretical lens of CVT, peer support could relate to a higher sense of control, maintaining the feeling of competence and promoting more positive emotions (Pekrun, 2024). The findings of Study II may also support this to some extent, as peer support was not associated with any of the studied emotions at a statistically significant level, and thus, may be perceived as more neutral. It has been suggested that when dealing with mistakes in the chemistry laboratory, students are more likely to provide one another with emotional support in comparison to teachers, who are more prone to focusing on the cognitive struggles and thus, simply correcting the mistakes (Keen & Sevian, 2022; Metcalfe et al., 2025). This could explain why students' emotions and perceptions of their competence may be better maintained in these situations. On the other hand, seeking help from peers might feel more acceptable in the sociocultural context of the laboratory (Keen & Sevian, 2022; Schechtel & Bongers, 2026). The effect of peer support may also have remained nonsignificant because of the variability in the quality of support students provide to one another. Some students can be very proficient in providing both instructional and emotional support, while others may struggle with doing so. However, prior research suggests that facilitating dialogue in the laboratory can enhance meaningful learning (Seery et al., 2024), and promoting engagement in collaborative interaction seems beneficial for learning from mistakes (Metcalfe et al., 2025). Plausibly, solving mistakes with peers can foster such dialogue and collaborative interaction among students.

To conclude, these findings contribute to the understanding that students' affective reactions to mistakes can significantly vary based on the mistake situation at hand. As such, not all mistakes should be attended to similarly, and the characteristics of the mistake situation should be taken into account. These findings also shed light on how the support itself can strongly impact students' affective experiences.

5.1.4 The role of contextual factors

Mistakes cannot be separated from the context, as the definition of a mistake as a deviation from the expected trajectory relies on contextual norms or expectations (Kipnis, 2011; Steuer et al., 2025; Tulis et al., 2016). Therefore, understanding the role contextual factors play in shaping students' affective experiences becomes relevant. Although all three sub-studies comprising this thesis are interpreted within the context of a chemistry laboratory course, the role of more-detailed contextual factors, such as the topic of the experiment, was explicitly modelled in Studies I and III.

Study I, situated in the laboratory setting, considered the roles of the topic of the experiment. Based on the findings, the topic of the experiment significantly impacted students' probabilities of making mistakes, as they were most likely to make mistakes in the pH-titration experiment. The topic was not associated with students' probabilities of experiencing OLMs, but it was related to the levels of OLM elements. In detail, students found the liquid-liquid extraction experiment the most interesting, and they perceived the highest skills in it, while it was also associated with the lowest challenge. In turn, pH-titration and buffer solution experiments were perceived as the most difficult. Prior research has also identified these topics as difficult for students (Sheppard, 2006; Tümay, 2016).

However, as students were more likely to make mistakes in the pH-titration experiment, the high challenge level does not seem to contribute to the likelihood of making mistakes alone. Perhaps, because the topics and procedure of the two difficult experiments were related, and all students had performed the pH-titration before the buffer solution experiment, they may have learned from their mistakes and were able to avoid repeating them (Ferjencik & Jalovy, 2010; W. S. Lee, 2020; Tulis et al., 2016) Other factors, such as students' misconceptions on the topic or the type of tasks included, could also impact (Käfer et al., 2019; Loibl & Leuders, 2019; Tulis & Fulmer, 2013). Similarly, Study III considered the role of the topic in the pre-lab on students' probability of making mistakes and their affective experiences. The results were fairly aligned with those from the laboratory, as students were most likely to make mistakes in the pre-lab on pH-titration. Pre-labs on the topics of liquid-liquid extraction and complexometric titration were perceived as the easiest, whereas the buffer solutions pre-lab was associated with the highest challenges.

In addition to the topic of the experiment, both Studies I and III focused on the role of the phase of the work. The findings of Study I suggest that in phases where students were required to integrate theory and practice, they were more likely to experience OLMs, a little lower interest, lower perceived skills, and significantly higher perceived challenges. Thus, in such instances, students' interest and skill seemed to remain high enough, but the significant increase in the challenge level contributed to experiencing high SE. The findings support what previous research proposes, more tightly connecting such phases to experiencing OLMs (Atabek-Yigit & Senoz, 2023a). In these phases of work, students were also more likely to make mistakes, which further reinforced the impacts on the OLM elements.

In turn, the findings of Study III suggest that students were more likely to experience OLMs, lower interest, as well as significantly lower perceived skills and higher perceived challenge towards the end of the laboratory session. This is probably because the experiments typically began with a practical activity, like measuring chemicals and performing analyses, and ended with activities that require integrating theory and practice, such as interpreting data, calculating results, and drawing conclusions. Thereby, the way chemistry experiments are typically built can influence students' affective experiences at different phases, and this underlines the need to have students engage in work even when they are nearing the finish line of the experiment. Nonetheless, for students to be able to do this in a 3–4-hour laboratory session, not every moment can be an OLM. Instead, also pauses, breaks, and phases of work that are less demanding in terms of not only cognitive but also affective requirements are needed (Chang, 2018; F. Kirschner et al., 2011).

Finally, Studies I and III together contribute to a deeper understanding of the role of context within the laboratory course, separating pre-labs from laboratory sessions. These contexts differed in multiple ways, as pre-labs were conducted online and laboratory sessions were in person. Students primarily performed the pre-labs individually, whereas the laboratory experiments were conducted in pairs. In pre-labs, students only received information on whether they had made mistakes in the activities after reporting their affective experiences, whereas in laboratory sessions, they self-reported their mistakes during previous activities and thus were aware of them before reporting their situational affective experiences.

However, across both contexts – pre-labs and laboratory sessions – students reported lower perceived skills and higher perceived challenges when they had made mistakes. What differed between these contexts was the level of interest in mistake situations. In the pre-labs, students' interest was not impacted by their mistakes at a statistically significant level, whereas during the laboratory sessions, mistakes were associated with a lower level of interest. Perhaps the decrease in interest could point to a maladaptive strategy that students use for coping with mistakes, linked to an experience of low control over the situation (D'Mello et al., 2014). In contrast, students may have been more unaware of their mistakes when reporting their affective experiences concerning the pre-labs, and as a result, they do not demonstrate similar maladaptive coping. Indeed, in the pre-labs, their experiences were more based on their self-reflections of success or failure (Chu, 2017; Pekrun, 2006).

Other factors that could have contributed to these differences are completing the activities alone vs. in pairs, or in the online environment vs. in person. Indeed, students performed the pre-lab tasks individually in an online learning environment, whereas the laboratory tasks were conducted in pairs and in person. There is a possibility that mistakes that occur in online learning environments do not feel as significant, reducing their influence on students' interest levels. In contrast, encountering mistakes in pairs may feel more prominent in comparison to encountering them alone, increasing their significance and the negative effects on interest. Moreover, during the pre-labs, students were, on average, less interested compared to the lab, and this could also explain why their levels of interest were not so prone to shifts in response to mistakes. The findings of Study III indicated that students' mistakes in the pre-labs may not carry over to the laboratory sessions, and this could also be attributed to the different contexts. It is indeed possible that the impact of mistakes does not strongly transfer between different learning environments, for example, from the online learning environment to in-person contexts.

Taken together, although there are similarities in students' affective responses to making mistakes across varying contexts, the context can provide deeper insights into the topic. The findings of the sub-studies suggest that multiple contextual factors, such as the topic and learning environment, have an effect. The topic largely impacts students' probabilities of making mistakes and their affective experiences in general, whereas the learning environment and its characteristics also seem to impact their affective responses to mistakes.

5.2 Theoretical reflections on the findings

The theoretical aims of the thesis were to contribute to the ongoing discourses of 1) the role of mistakes in learning (see e.g. Narciss & Alemdag, 2025; Steuer et al., 2025), and 2) students' affective learning in chemistry laboratory courses (see e.g. Agustian et al., 2022; Seery et al., 2019). In this section, the main findings of this thesis are discussed in relation to these aims. Accordingly, the section is divided into two subsections: one that more generally addresses the role of mistakes as a part of learning, and another that provides insights into how the learning objectives for chemistry laboratory education could be expanded based on the main findings. Thus, the first subsection focuses on reframing mistakes, and the latter focuses on reframing chemistry laboratory education and its objectives.

The theoretical reflections presented in this section form a basis for the practical implications, which will be introduced later in section 5.4. Therefore, this section focuses more on the theoretical reframing of mistakes and laboratory education, refraining from making more concrete calls for action.

5.2.1 Mistakes as a part of learning

In alignment with previous research, the findings of this thesis explicitly frame mistakes as frequently occurring and essentially inseparable from chemistry laboratory work (Galloway et al., 2016; Kipnis, 2011; Nunes et al., 2022). This emphasizes the need to consider them as a distinctive learning phenomenon rather than an unwanted but inevitable by-product of laboratory work (see also Frese & Keith, 2015; Tulis & Dresel, 2025). Looking ahead, future research on mistakes ought to shift away from how to avoid them and move toward examining how to effectively support students in navigating such situations (Tulis & Dresel, 2025).

Second, in this thesis, students' affective responses to mistakes were examined through a cognitive-motivational framework, aligning with Pekrun's (2006, 2024) CVT. Such a framework situates individuals in the context and allows for touching on both cognitive and sociocultural perspectives on learning. The findings of all three sub-studies show that while students' affective reactions to mistakes are, in general, relatively negative, there is significant variance in them. As described in the '5.1 Main findings' section, this variance can be explained by individual, situational, and contextual factors. Thereby, approaching this phenomenon through a theoretical lens that considers multiple perspectives on learning can be recommended.

Furthermore, this thesis does not approach mistakes as something objective, nor does it try to identify all students' mistakes. Instead, in Studies I and II, it is focused on students' subjective experiences of encountering them. To this date, such an approach has not been widely adopted in the research field, particularly among quantitative studies – yet it is arguably valid when focusing on students' affective responses. Indeed, students emotionally respond to their subjective experiences (Pekrun, 2006). While they may miss some instances that would be "objectively" identified as mistakes (Atabek-Yigit & Senoz, 2023b; Hämmerle et al., 2025), such instances are likely rather irrelevant in shaping students' affective experiences in the situation. After all, emotions are, by definition, triggered by specific stimuli (Pekrun et al., 2018; Shuman & Scherer, 2013).

Moreover, in relation to previous research approaching mistakes as subjective experiences (see e.g. Tulis et al., 2018; Huangfu et al., 2023), this thesis contributes to the field by also approaching mistakes as situation-specific instances that can influence one's situational affective experiences rather than something that has stable impacts on trait-like emotional experiences (see also Schmid et al., 2025). As was mentioned, students' affective responses varied greatly between situations, and measuring experiences on-task and in situ allowed for detecting this variance. This approach does not rely on students' recall, as the emotional experiences are reported during the occurring learning situations (e.g. Kitterød & Lyngstad, 2005). Although this relatively new, situational approach was used, the findings of the three sub-studies are mainly aligned with those relying on the recall of retrospective experiences (e.g. Schechtel & Bongers, 2026). However, the situational approach provided new perspectives into, for example, gender differences and how stable trait-like motivational dispositions and academic performance can influence students' affective responses to mistakes. Thus, the findings of this thesis bring new depths into the discourse on the role of mistakes in students' (affective) learning processes.

Indeed, even though mistakes generally appear to be related to negative affect, they could also have a potentially engagement-promoting role. Along these lines, Galloway and colleagues (2016) explain that some students find emerging challenges as motivators and learning opportunities in the chemistry laboratory. This is supported by the findings of this thesis, suggesting that mistakes may provide students with the required challenges for optimal learning (B. Schneider et al., 2016), and they may also be associated with higher emotional activation. Such an activation is perceived as crucial for student engagement in learning situations, and it can enhance learning by mitigating the negativity of students' emotional responses to mistakes (Corwin et al., 2022; Pekrun, 2006). Thus, the findings point to a direction where mistakes are interpreted as a plausibly motivating phenomenon rather than something inherently negative (see also Frese & Keith, 2015).

Finally, in this study, mistakes were operationalized as momentary departures from expected trajectories associated with versatile emotional experiences. The findings support this, for example, by indicating that students' activity-related frustration increased even more than their plausibly failure-expectancy-related anxiety, framing mistakes as a situated learning phenomenon. Moreover, this highlights the need for a better understanding of the dynamics between mistakes and failure. Importantly, students' own conceptions of the differences and similarities between these two phenomena should be looked at more in depth. Generally, in the literature, students' emotional responses to mistakes are often regarded as reflecting their outcome emotions triggered by retrospective failure (Agustian et al., 2025b; Corwin et al., 2022; Pekrun, 2006, 2024; Schechtel & Bongers, 2026). Alternatively, as was done in this thesis, anxiety experienced in a mistake situation may be understood as a prospective achievement emotion, reflecting the expectancy of future failure, with the assumption that encountering the mistake in itself is not interpreted *as failure* (Pekrun, 2024). As such, the mistake may (or may not) be a threat to reaching the students' goals, depending on the activities and success that follow. This alternative perspective could help frame mistakes as a more situational and contextual phenomenon, differentiating them from their inherently more negative failure counterparts (Schechtel & Bongers, 2026; Simpson & Maltese, 2017).

5.2.2 Expanding the learning objectives for chemistry laboratory education

As described in the theoretical framework chapter, the objectives of science education can be conceptualized as threefold, consisting of learning science, learning about science, and learning to do science (Hodson, 2014) – all of which are in some way related to mistakes. First, making mistakes lies at the heart of the third objective, learning to do science (Allchin, 2012; Kipnis, 2011), which has also been established as the primary pursuit of chemistry laboratory education (Agustian, 2022; Seery, 2020). Therefore, if students ought to learn to do science, they ought to learn to make mistakes in the chemistry laboratory. The empirical findings of the sub-studies suggest that this objective is well manifested in terms of making mistakes, as students continuously reported encountering them.

Second, the findings of Studies I and II propose that students not only make but can also identify different types of mistakes during laboratory work, such as conceptual and experimental, careless and knowledge-gap-based ones. Identifying and engaging with these different mistake types can support students' understanding of the nature of science (Allchin, 2012, 2020), which in turn supports the objective of learning about science (Hodson, 2014). Additionally, simply understanding what an intrinsic part of laboratory work mistakes are and how frequently they can occur is aligned with the objective of learning about science in the chemistry laboratory.

Third, although it was not explicitly touched upon in any of the empirical sub-studies, mistakes can also be harnessed to promote the learning of disciplinary content knowledge. For example, productive failure literature (see e.g. Kapur, 2008; Kapur & Bielaczyc, 2012) and learning from errors research (see e.g. Metcalfe, 2017; Metcalfe et al., 2025) suggest that mistakes, representing a discrepancy between one's expectations and the actual outcome, can trigger conceptual conflicts, which can ultimately lead to conceptual change and learning.

Nevertheless, although mistakes are well-represented within all three objectives, some important aspects are left unaddressed. The findings of the sub-studies emphasize that engaging in laboratory work is an emotional endeavour and dealing with mistakes while doing it can be emotionally challenging. This portrays undergraduate chemistry laboratories as affective learning environments and places to practice meta-affective learning, that is, turning initially negative affect into a positive meta-affect through reappraisal (Radoff et al., 2019; Sharabi & Roth, 2025). This perception of the laboratory is also well-supported by previous research, suggesting that the affective domain should not be overlooked in chemistry laboratory education (Agustian, 2022; Agustian et al., 2022, 2024; Galloway et al., 2016; Schechtel & Bongers, 2026). With such notions, Hodson's (2014) three dimensions of learning objectives could be expanded to include an additional objective focused on *learning to navigate scientific challenges*.

This proposed dimension would go beyond simply dealing with scientific mistakes, involving, for example, engaging with uncertainty and doubt, embracing challenges, solving complex problems, and encountering failure – all things integral parts of science (e.g. Firestein, 2016; Henry et al., 2019; Keen & Sevian, 2022; Simpson & Maltese, 2017). As such, students would develop resilience and improve in adaptivity by handling the inherent uncertainties of scientific practices, reflect on their emotions and attitudes toward science by learning through cognitive and emotional struggles, develop skills and competencies required to navigate scientific problems, as well as share struggles, seek support and collaborate to overcome the challenges in a scientific community. Importantly, this objective addresses the neglected affective domain of laboratory learning (Agustian, 2022; Galloway et al., 2016) but is not limited to building positive affect toward science, nor does it overlook the intertwined cognitive aspects. It portrays science as something that requires perseverance, grit, and resilience, and cannot be completely mastered by merely understanding it (see Nunes et al., 2024; Simpson & Maltese, 2017).

Prior research has not yet identified these as the typical learning outcomes of undergraduate chemistry laboratories, although some of these could be somewhat regarded as representing the identified accomplishments of higher-order thinking skills, epistemic learning, transversal competencies, and affective outcomes (Agustian et al., 2022; Seery et al., 2024). Nevertheless, establishing these as something inseparable from learning scientific disciplines could deepen their significance for chemistry laboratory education. In this regard, explicitly defining the additional domain of learning to navigate scientific challenges as a learning objective for chemistry laboratories should, in terms of constructive alignment, contribute to these outcomes (see also Seery et al., 2024). Adopting this as an explicit learning objective could also help reframe mistakes as acceptable and potentially even positive, reducing their stigma and students' fear of failure (Nunes et al., 2022; Schechtel & Bongers, 2026). Ultimately, this could even support the development of students' science identities (Simpson & Maltese, 2017).

Thus, in future research, it is advisable to consider the central role of developing perseverance as a scientist, namely learning to navigate scientific challenges, as a distinct learning objective for the chemistry laboratories. This would simultaneously emphasize the importance of considering the affective learning domain in chemistry laboratory education, contributing to the ongoing discourse on the reform of chemistry laboratories (see e.g. Agustian, 2022; Galloway et al., 2016; Seery et al., 2019).

5.3 Methodological reflections

This section reflects on the methodology used in this thesis. The methodological aims were to contribute to the body of research on the role of mistakes in learning by approaching them on task and in situ (Narciss & Alemdag, 2025; Tulis & Dresel, 2025) and to model students' intra- and interindividual variance of in-situ affective experiences using advanced statistical methods. First, the contributions relating to the data collection design are highlighted, and then, contributions regarding the analytical approaches are discussed. Both subsections explore the potential of this methodology, rooted in the educational psychology tradition and applied in the context of science, or more specifically, chemistry education. Ultimately, this research bridges several fields of study, including science and chemistry education as well as educational psychology and learning sciences, which are still relatively seldom considered together. Consequently, it is important to note that the integration of their respective theoretical frameworks and methodologies is still in a tentative phase, but it arguably demonstrates significant potential for future research.

5.3.1 Data collection approach

The primary data collection method in all three sub-studies comprising this thesis was ecological momentary assessment (EMA). This "person-in-context" approach provides highly contextual and situated data, based on students' subjective reporting during real learning situations in an authentic environment (Carson et al., 2010; Kitterød & Lyngstad, 2005; Sinatra et al., 2015). The use of this kind of data collection design for the purposes of educational research has only become more widespread relatively recently, mainly in the field of educational psychology, while its use has remained fairly infrequent across science education contexts (Mölsä et al., 2022; Sinatra et al., 2015; Smith & Alonso, 2020). Nevertheless, as can be seen based on the findings of this thesis, it provides valuable information about learning as a process within real-life contexts, such as the undergraduate chemistry laboratory here.

Indeed, in the chemistry laboratory context, studies using EMA data collection methodology (or similar, such as the experience sampling method) have been particularly rare (see Atabek-Yigit & Senoz, 2023a). However, this thesis supports its good applicability in investigating laboratory education. Even though the implementation of an EMA data collection requires careful planning (see e.g. Fritz et al., 2024), such data collections can be integrated relatively easily and seamlessly into the overall implementation of the targeted laboratory courses. As such, they provide a good window into collecting students' contextually nuanced experiences across multiple time points, reflecting on students' authentic learning processes during the course.

In this study, the EMA data collection points were connected to a specific phase of the work, as an alternative to the more traditional time-based approach (cf. Inkinen et al., 2019; Vilhunen et al., 2022). Students responded to the EMA questionnaires at different points in time, but this approach allowed for connecting the reported experiences to specific activities, completely based on the laboratory work instructions. This made the consideration of contextual factors, such as whether the phase of work was primarily experimental or required integrating theory and practice, more straightforward. Additionally, this approach is, in general, less likely to interrupt students' workflow and therefore unintentionally influence their (affective) experiences. Based on these notions, it appears feasible for utilization in future research and across other contexts as well.

Furthermore, the EMA data collection was not limited to the laboratory sessions but extended to the pre-lab activities (cf. Atabek-Yigit & Senoz, 2023a). This enabled capturing students' experiences throughout the entire course, across all different types of learning activities, in a comparable way. In Study III, the pre-lab experiences were connected to students' experiences in the consecutive laboratory sessions through this approach. This provides new insights into the role of pre-labs, not just as situated phenomena, but also regarding lagged over-time effects on later instances (see also Agustian & Seery, 2017). Looking ahead, future research could also focus on within-session trajectories in students' experiences through the time-sensitive nature of EMA data.

Overall, EMA designs are less prone to recall bias and individuals overestimating the duration of their emotional response, which have been identified as significant shortcomings of measuring emotional responses retrospectively (Hektner et al., 2007; Kitterød & Lyngstad, 2005; Wilson & Gilbert, 2005). Based on the results of Study III, students' emotional responses to mistakes captured with an EMA design are of a relatively short-lived nature, as their effects do not carry over to later instances. This emphasizes the need for subtle data collection approaches that can detect momentary fluctuations in students' affective trajectories, such as the EMA used in this study, particularly in emotionally rich contexts. Capturing students' affective responses to certain triggers with this kind of approach can put the intensities of the effects into more realistic proportions; for example, here, students are not merely focusing on how the mistake made them feel, but instead, report their broader, lived affective experiences.

This data collection approach allowed for gathering quantitative, situational, and context-sensitive data about students' mistake experiences in the chemistry laboratory. Such in-situ measures of students' affective responses to mistakes have been extremely few in numbers in the body of research regarding mistakes (Keen, 2021; Schechtel & Bongers, 2026; Schmid et al., 2025; Soncini et al., 2025), and most of the previous research has still relied on either recall (e.g. Corwin et al., 2022; Reindl et al., 2020; Soncini et al., 2025; Tulis et al., 2018), or qualitative data (e.g. Schechtel & Bongers, 2026). This thesis contributes to the research gap with three sub-studies, all utilizing in-situ EMA data.

Overall, EMA designs, consisting of repeated self-report measures, are suitable for capturing the intraindividual, situational variance across students' emotional responses to mistakes that other approaches often overlook (Hektner et al., 2007; Kitterød & Lyngstad, 2005). The design comes with an ability to capture learning as a process, detecting variation in students' experiences across authentic contexts. As can be seen based on the findings, this is crucial for capturing the complex nature of mistake situations, varying based on factors such as the type and cause of the mistake, as well as the form of support sought. Therefore, based on the findings, it is advisable to utilize situational measures to address also subtle fluctuations in students' affective experiences – particularly in the research domain focusing on mistakes or similar situated phenomena.

5.3.2 Analytical approach

The research data were analyzed using the multilevel structural equation modeling (MSEM) framework in all three sub-studies. In terms of methodology, one aim of the thesis was to model students' inter- and intraindividual variation in their in-situ affective experiences and responses to mistakes, which the MSEM framework is well-suited to capture. Indeed, using such statistical analyses to investigate interactions between and within students, the variation in students' affective experiences can be distributed across multiple levels, reflecting, for example, intraindividual, within-person variation, and interindividual, between-person variation. The MSEM models specified in the sub-studies were focused on the roles of individual, situational, and contextual factors in shaping students' situational affective responses to mistakes. Although simple regression models may also be able to reveal how situational factors (here, type and cause of mistake, as well as the form of support sought) predict dependent outcomes (here, situational engagement and emotions), an MSEM approach provides a more nuanced analysis framework, accounting for between-person variance in the outcomes (Lüdtke et al., 2008; Muthén, 1994; Preacher et al., 2010).

Indeed, what is particularly beneficial in MSEM models is that the variance can be distributed across multiple levels. Therefore, even when the research questions are focused primarily on one level, the effects on other(s) are also considered or controlled for. Therefore, in these models, the effects can be more easily attributed to the correct level and connected to the statistically meaningful variables. For example, in this thesis, individual-level effects were distinguished from situational-level effects in all three sub-studies, and topic-level effects were distinguished from these two in Study III. In simpler statistical models, such effects often remain hidden. Focusing merely on individual-level associations can conceal a great variability in individuals' experiences (see e.g. Tulis et al., 2018), whereas the MSEM framework can capture and control for it. On the other hand, modeling an interaction with the assumption that all individuals respond to certain triggers in the same way (see e.g. Atabek-Yigit & Senoz, 2023a) overlooks many relevant individual differences between students, which is again something that the MSEM can capture and control for.

Regardless, even though MSEM could be suitable for many science education research purposes, it is still considerably rarely used as an analytical framework in the field, probably in part due to the low utilization of EMA-type data. Indeed, science educators are generally interested in how learners' cognitive, affective, and behavioral processes unfold across versatile learning situations, and how specific contextual triggers, such as the types of activities, teacher support, or peer interactions, can shape their cognitive, affective, and behavioral development in real time (Duit, 2007). While statistical analyses within this framework are more complex and thus require slightly larger datasets, a between-level sample size of 50 (e.g. individuals) can already be sufficient if there is an adequate number of within-level observations (e.g. situations) (Maas & Hox, 2005). Such a sample size is feasible in many university-level (laboratory) courses, indicating that future research could effectively utilize similar data collection and analytical frameworks as those that were employed in this thesis. This approach can be recommended, as the methods used in this study not only appeared promising but also yielded rich results across the three sub-studies.

Additionally, it is often relevant to distinguish how stable individual characteristics impact these dynamics. Therefore, particularly in modeling how such individual-level factors may moderate the dynamics of situational-level interactions – for example, emotional responses to mistakes – the MSEM framework is highly beneficial. Here, in Study II, MSEM with random slopes was utilized to capture such moderation dynamics, focusing on how stable individual traits shape students' situational, emotional responses to mistakes (Hall & Malmberg, 2020). Based on the analysis, groups of students who may require additional support with emotional regulation in mistake situations were successfully identified. Overall, MSEM with random slopes seems to be a functional approach to studying students' affective responses to certain situational triggers, such as mistakes.

Similarly, based on the findings of Study III, MSEM models resembling cross-lagged panel models and utilizing time series data seem promising for capturing students' emotional trajectories over time (see also Kearney, 2017). In this study, this was done from pre-lab activities to laboratory sessions, as the pre-lab experiences were treated as predictors of students' laboratory experiences. As such, the two types of activities were combined in the same statistical model. Here, this approach was able to provide new insights into how students' previous experiences can influence later experiences. In the future, similar analytical approaches could be extended to examining students' emotional trajectories from, for example, lesson to lesson. Nevertheless, like the other analytical approaches within the MSEM framework, this method has not been employed very widely in the field of science education research so far, but broader use could be recommended.

Overall, these analytical approaches seem to provide nuanced information across multiple levels of interest. They can capture learning processes in authentic environments, whereas in comparison, controlled experiments with pre- and post-test settings only tend to capture small changes over time without saying much about what happens in between. To address this issue, future research might consider combining the traditional pre- and post-measures with these dynamic and nuanced situational experiences. However, although these methods show good potential for future research, their broader applicability and robustness need to be evaluated further. Finally, in conclusion, the MSEM framework adopted in this thesis appears highly beneficial for future research, not only in terms of mistake research but also more broadly for science education research.

5.4 Practical implications

This section addresses the practical implications of the findings. The practical aims were to contribute to the reform of chemistry laboratory education (see also e.g. DeKorver & Towns, 2015; Keen & Sevian, 2022; Seery et al., 2024), to provide educators with new insights on how to support students' learning in chemistry laboratory courses, particularly in situations involving mistakes (see also Agustian et al., 2025b; Keen & Sevian, 2022), and to gain perceptions on how these matters should be addressed in teacher education (see also Lutovac, 2019; Simpson et al,. 2025).

As per the practical aims, the implications are divided into three dimensions: 1) the broader reform of chemistry laboratory education, 2) supporting students' learning in the chemistry laboratories, particularly in situations involving mistakes, and 3) implications for teacher education. The first subsection addresses ways in which the conceptualization of undergraduate chemistry laboratories could be refined, the second provides more concrete suggestions for educators on how they might improve their teaching based on the results of this thesis, while the third presents some ideas on how this matter should be addressed as a part of teacher education. However, the third subsection is tightly interrelated with the second, as many of the implications presented in the latter could be applied to the former.

The practical implications presented in the following section are tightly interconnected with the theoretical reflections on the empirical findings. Indeed, section '5.2 Theoretical reflections on the findings' presents the theoretical foundations for the more concrete suggestions introduced in the following section. Subsection '5.2.2 Expanding the learning objectives for chemistry laboratory education' presents the theoretical foundation for subsection '5.4.1 Reform of the chemistry laboratory education', and subsection '5.2.1 Mistakes as a part of learning' presents the theoretical foundation for subsections '5.4.2 Supporting students' learning in chemistry laboratories' and '5.4.3 Implications for teacher education'.

5.4.1 Reform of the chemistry laboratory education

Based on the findings of this thesis, several actions which could be undertaken to improve undergraduate chemistry laboratory education are presented in this section. First, they are introduced in more detail, while the section concludes with an overview Table 7, which summarizes the suggestions.

In line with the current discourse on the undergraduate chemistry laboratory education, the empirical findings of this thesis highlight that the chemistry laboratory functions as an emotional environment, and the affective domain should be recognised as a crucial component of this context (see also DeKorver & Towns, 2015; Keen & Sevian, 2022; Seery et al., 2024). As was suggested in the subsection entitled '5.2.2 Expanding the learning objectives of chemistry laboratory education', learning to navigate scientific challenges, related to all learning domains, should be emphasized. Curriculum developers and teachers should identify and establish this as an explicit learning goal. Teachers should also ensure that they communicate this goal to the students, for example, at the beginning of the laboratory course. This could support not only students' learning (Darabi et al., 2018; Keen & Sevian, 2022; W. S. Lee, 2020) but also the development of their resilience and persistence (Frese & Keith, 2015; Simpson & Maltese, 2017), positive affect toward learning (Tulis et al., 2018), and science identities (Simpson & Maltese, 2017).

As was revealed by the findings of this thesis, mistakes have a central role, which should be better recognized and taken into account when designing chemistry laboratory education. Prior findings suggest that currently, not all laboratories allow students to make mistakes or fail (Schechtel & Bongers, 2026), which deeply undermines the suggested learning goal of learning to navigate scientific challenges, and may even give students a completely wrong impression about what science is (Allchin, 2012, 2020; Hodson, 2014). To support this reform, mistakes should be reframed as something distinct from failure. Indeed, failure and success are linked to the broader goals and objectives (Corwin et al., 2022; Henry et al., 2019), and as learning to navigate scientific challenges requires encountering such challenges, dealing with mistakes – and ultimately with failure – within chemistry laboratory education functions as a prerequisite for achieving this goal. Hence, the laboratories should be established as places where uncertainty, doubt, and struggles are not only accepted but also embraced (see also Agustian et al., 2025b; Galloway et al., 2016; Schechtel & Bongers, 2026; Vilhunen et al., 2021).

In practice, this could mean shifting the focus away from obtaining some specific, predetermined results, moving towards open experimentation, observations, and explanations (see Krajcik et al., 1998; Renninger et al., 2018; Sadeh & Zion, 2009). Navigating mistakes should be clearly articulated as a learning goal of laboratory education instead of something to be avoided (see also Miller &

Krajcik, 2019). It might be beneficial to point out to students that even though chemistry is often considered an exact science, laboratory work is tentative by nature, and it entails a lot of uncertainty, mistakes, and trying again. Encountering mistakes and productively dealing with them ought to be a sign of a successful learning experience, even more so than achieving “correct” results. In this kind of learning framework, students’ performance should not be evaluated based on the results they yield, but rather on how they make sense of their observations and explain what they could have done differently. As such, students may also develop stronger skills in terms of scientific sensemaking, making observations, and constructing explanations (Krajcik et al., 1998; Sadeh & Zion, 2009). While unexpected results should never be framed as a failure, students should be celebrated for their critical thinking rather than finishing the work and getting the “correct” results (Schechtel & Bongers, 2026).

It is also important to reconsider the limited timeframes dedicated to laboratory sessions, as many students seem to avoid making mistakes in order to finish the laboratory work on time (see e.g. DeKorver & Towns, 2015; Krajcik et al., 1998; Schechtel & Bongers, 2026). Troubleshooting and trying again should either be possible within the laboratory hours, or yielding specific results should not be required. Furthermore, dedicating time for all students to retry, regardless of their success on the first try, could not only even out the time students use to finish the experiment but also allow the exploration of alternative approaches. Students would then have the opportunity to explore – to adjust the parameters in the experiment and learn how they influence the outcome – which might promote learning outcomes such as critical thinking and other transversal competences (Renninger et al., 2025; Sadeh & Zion, 2009).

Another way to shift the focus from having to achieve the “correct” results could be concluding each laboratory session with an instructional classroom discussion on the findings. All students, pairs, or groups could experiment as usual, documenting their observations and constructing explanations. As, based on the findings of this thesis, students make a lot of mistakes, some of these experiments would very likely yield unexpected results. By collectively discussing the findings and constructing explanations at the end of the laboratory session, all students would have the opportunity to deal with the expected and unexpected results. This would provide the students, who traditionally “succeeded” in the experiment and yielded expected results, with the chance to also deal with uncertainties and navigate scientific challenges, while those students, who traditionally “failed” and yielded unexpected results, would also get the chance to learn what others may have done differently and what might have worked better, as well.

Moreover, this study, among some previous findings (Atabek-Yigit & Senoz, 2023a; Inkinen et al., 2020), reveal that students perceive the challenge level of laboratory work to be relatively low. Moderate challenges are necessary for enabling students to experience both difficulties and mistakes (Corwin et al., 2022), while the low challenge can compromise student engagement (B. Schneider et al., 2016). The empirical findings also point to some actions that could be taken to overcome this challenge, or rather, the lack of challenge.

The findings of Study I reveal that students' perception of the challenge was higher in instances where they had to integrate theory and practice, and they were more likely to experience high situational engagement. In such phases of work, students were also more likely to make mistakes, which reinforced the increase in perceived challenges but was not directly linked to experiencing high situational engagement in itself. Studies I and II propose that when students are navigating problems with their peers, they may be more likely to actively engage with the challenges. In addition, the findings of Study III show that the perceived challenge level decreased over the laboratory course, suggesting that a steady increase in the difficulty level of the learning tasks could be beneficial for maintaining an optimal challenge level and supporting students' continuous development throughout the course.

Precisely, the findings of Study I encourage promoting theory-practice connections during laboratory work to enhance student engagement (see also Atabek-Yigit & Senoz, 2023a). This could be done by requiring students to do calculations to advance in their work, posing students with questions about the theoretical background regarding the methods and results, including prompts to think about the underlying chemical concepts, or allowing students to design (some sections of) their own experiment (e.g. Danial et al., 2025; Renninger et al., 2025; Sadeh & Zion, 2009). Per se, previous studies reveal that in cases where the laboratory experiment consists of more open inquiry tasks, associated with higher levels of student autonomy, the challenge level of the entire laboratory experiment, including non-computational phases, can be higher (Lamminpää & Vesterinen, 2018; Sadeh & Zion, 2009). As was described earlier, these open inquiry tasks may also support reframing mistakes.

Additionally, if students have a choice in framing the laboratory activities, they are more likely to experience high situational engagement (Schmidt et al., 2018). Essentially, mistakes could be viewed as triggers for student autonomy in more recipe-style laboratory work (Galloway et al., 2016). Making mistakes indeed deviates students from the expected trajectory of the pre-designed steps of the laboratory work, enhancing their emotional activation and perceived challenges, but also suddenly increases their opportunities and choices. As such, mistakes may be considered promoters of inquiry (Agustian et al., 2025a, 2025b), also in more traditional expository-type laboratory courses, once again highlighting their crucial importance.

Finally, the findings of Study III also address the central role of the pre-lab activities in terms of the affective learning domain. The findings support the idea that pre-labs are important for preparing students for the affective requirements of laboratory work, originally suggested by Agustian and Seery (2017). They set the tone for the entire laboratory work, can foster confidence, and trigger interest in learning more. The empirical findings indicate that high situational engagement in pre-labs predicted high situational engagement in the laboratory, and so did interest, skill, and challenge experiences. In addition to these consecutive effects, feeling skilled in the pre-lab promoted higher interest in the laboratory, and similarly, higher perceived challenge in pre-lab predicted higher interest in the laboratory. Thereby, pre-labs are important beyond familiarizing oneself with the topic and reducing the cognitive load of laboratory work (Agustian & Seery, 2017), as they can shape affective learning in the lab, as well. Hence, educators should focus on providing students with sufficient challenges in the pre-labs, but keep in mind that fostering confidence and a sense of competence can also support affective learning in the laboratory. Although the emotional experiences seem to carry over to the laboratory sessions, mistakes need not be avoided in the pre-labs either, as the affective reactions would appear to have subsided by the time students enter the laboratory.

Table 7. An overview of the recommended actions for reforming undergraduate chemistry laboratory education.

Expand the learning goals of laboratory education
• Establish *learning to navigate scientific challenges* as an explicit learning goal in the curriculum (also see section 5.2.2) • Explicitly communicate this learning goal to the students • Emphasize the tentative nature of laboratory work
Create a learning environment that allows making mistakes, and reframe mistakes as something distinct from failure
• Reframe mistakes as valuable promoters of student agency and inquiry • Utilize open experimentation, making observations, and constructing explanations over chasing predetermined results • Dedicate time for all students to retry the experiment and see how adjusting parameters affects, regardless of how they succeeded on the first try • Promote instructional classroom discussion on the expected and unexpected results • Do not evaluate students' performance based on the results they yield • Celebrate students for their critical thinking rather than finishing the work
Provide students with adequate challenges

• Promote theory and practice integrations
  o Require students to do calculations to advance in their work
  o Pose students with questions about the theoretical background regarding the methods and results
  o Include prompts to think about the underlying chemical concepts in the work instructions
  o Allow students to design (some sections of) their own experiments
• Allow students to think for themselves before helping them
  o Do not rush to help students before they even ask for help
  o Do not give direct answers right away
  o Encourage students to navigate problems with their peers
• Increase in the difficulty level of the experiments steadily across the course

Design pre-labs that promote engagement
• Design pre-labs that are sufficiently challenging • Allow students to make mistakes on the pre-labs • Design pre-labs that address the affective dimensions of learning and foster confidence and a sense of competence

5.4.2 Supporting students' learning from mistakes in the chemistry laboratory

This section presents several concrete actions that educators should take, based on the findings, to help students productively deal with mistakes. Initially, these actions are described in more depth, followed by a summary of the proposed actions and their recommended timing in Table 8.

First and foremost, the findings reveal that mistakes are an integral part of doing science, and students frequently encounter them in chemistry laboratory courses. Thus, they should feel comfortable navigating mistake situations in order to facilitate engagement and, ultimately, learning (cf. Miller & Krajcik, 2019). The findings of Study III even seem to cautiously suggest that although students' momentary affective responses can be fairly strong, they can emotionally overcome the mistakes in a relatively short time, portraying them as far from detrimental and nothing to be avoided. Nonetheless, this does not mean that mistakes should not be taken seriously or that they cannot negatively affect learning.

It is relevant to keep in mind that performance and learning are dissociable, and lower momentary performance, indicated by, for example, making mistakes, does not necessarily indicate hindered learning but often leads to better long-term learning outcomes (Darabi et al., 2018; Soderstrom & Bjork, 2013). Evaluating learning as a process should not entail focusing on students' success or failure at every moment (Kipnis, 2011). Thus, although students and teachers may commonly be very disinclined to do so, they should view making mistakes not only as an unavoidable part of the learning process, but also as highly beneficial (Darabi et al., 2018; Kapur & Bielaczyc, 2012; Soderstrom & Bjork, 2013). This may help students to get freed from their fear of failure, as it is easier for them to shift their learning goals away from avoiding mistakes (Agustian et al., 2025b; DeKorver & Towns, 2015; Nunes et al., 2022).

Overall, how mistakes are framed in the laboratory is a crucial factor in how students perceive them (Blumenfeld et al., 1991; Nunes et al., 2024; Wan et al., 2023). In a learning context where mistakes are positively framed, students are more likely to engage in meta-affective learning (Radoff et al., 2019), and to subscribe to more positive error beliefs (Huangfu et al., 2023; Steuer et al., 2013; Tulis et al., 2018). These beliefs, in turn, play an important role in the quality of students' reactions to mistakes (Huangfu et al., 2023; Tulis et al., 2018). More positive beliefs could indeed be called for, as the findings of all three sub-studies reveal that students' reactions to mistakes are, on average, rather negative.

In practice, a teacher can frame mistakes positively by normalizing them, even encouraging students to make mistakes as a part of the learning process (Blumenfeld et al., 2004; Keith & Frese, 2008; Wan et al., 2023), indicating learning opportunities based on students' mistakes and using their professional knowledge of students' misconceptions to enhance learning (Käfer et al., 2019), not evaluating students negatively based on their mistakes (Käfer et al., 2019; Steuer et al., 2013), and, importantly, differentiating them from failure in their speech (Frese & Keith, 2015; Soderstrom & Bjork, 2013). Additionally, illustrating how frequently mistakes can occur in similar undergraduate chemistry laboratory courses – even in almost one third of all learning situations – and showcasing different examples of mistakes that have previously occurred may be valuable. However, framing mistakes positively only after they have happened seems inefficient, placing an undue emphasis on the fact that a mistake has occurred (Wan et al., 2023). Instead, this broad framing could be done at the beginning of the laboratory sessions, and in mistake situations, teachers might focus more on scaffolding the specific erroneous idea (Wan et al., 2023).

Additionally, while this may seem like a minor detail, distinguishing between failure and mistakes could be advantageous (see also Blumenfeld et al., 1991). This stems from the definitions adopted in this thesis, characterizing failures as inherently negative, while the emotional valence of mistakes is viewed as more situational (Schechtel & Bongers, 2026; Simpson & Maltese, 2017; Tulis et al., 2016). By understanding these concepts as distinct, students may come to first accept the less inherently negative mistakes as normal and even positive, eventually facilitating the acceptance of the inherently negative failures as well (see also Radoff et al., 2019). Hence, it is not only about how these instances are framed but also referred to when students are building their resilience to confront and navigate such situations (see also Lutovac, 2019; Simpson et al., 2025).

Moreover, how teachers frame and talk about mistakes also impacts the classroom or laboratory culture and the error climate of the learning environment (Dresel et al., 2025; Soncini et al., 2022; Steuer et al., 2013; Wan et al., 2023). In a mistake-friendly environment, students are more likely to adaptively react to mistakes and subsequently learn more (Dresel et al., 2025; Soncini et al., 2022; Steuer et al., 2013). Peer reactions also shape the error climate (Steuer et al., 2013), while they are, in turn, also shaped by the framing of mistakes in the classroom. In addition to the positive framing of mistakes, the error climate of the learning environment is reflected in the pedagogical practices used, such as analyzing mistakes with students and providing them with instructional support after they have made mistakes (Steuer et al., 2013).

Although this instructional cognitive support is important for, for example, the students to be able to operate within the zone of proximal development (Vygotsky, 1978), focusing solely on correcting the mistakes and completely neglecting students' affective needs can compromise meaningful learning (Galloway et al., 2016; Keen & Sevian, 2022; Metcalfe et al., 2025). This is particularly true as, based on the findings of Studies I and II, students' emotional landscapes seem to be particularly negative in instances where they have received support from the teacher in solving the mistake. Therefore, in addition to supporting students with their cognitive struggles, their emotional needs also need to be met. This could be achieved by providing students with affective scaffolding, that is, emotional support expressed in the moments of struggle (Blumenfeld et al., 2004). This emotional support is, in many ways, similar to empathy (Brutto et al., 2025). Luckily, as chemistry laboratories are abundant in social, interactional, and discursive dynamics (Agustian et al., 2025a), they offer learning environments where expressing empathy is relatively easy (Brutto et al., 2025). This empathy, and thus emotional support in mistake situations, can be expressed in numerous ways, depending on the key factors identified in this thesis, including the individuals participating in the interaction, situational factors in which the interaction occurs, and the broader context of the learning environment (see also Brutto et al., 2025; Keen & Sevian, 2022). Although one-size-fits-all suggestions cannot be provided, some concrete examples of what the emotional support could look like are presented next.

First, emotional support may include acknowledging and affirming students' emotions across all situations, including mistakes (Sharabi & Roth, 2025; Simpson et al., 2025). It may come across as letting the student know that you see how they are feeling and that their feelings are valid, normal and sensible (e.g. Blumenfeld et al., 2004). In addition, short, genuine, and encouraging phrases in such instances can be valuable; for example, cheering on students to continue and letting them know they are doing well. Pay attention to the skills and competencies that the students demonstrate rather than immediately pointing out what was wrong. On the other hand, in some instances, approaching the situation with humor can also be suitable (Brutto et al., 2025; Lamminpää & Vesterinen, 2018). Humor has been identified as a common emotion regulation method among peers in the face of mistakes and failure (Agustian et al., 2025b; Brutto et al., 2025; Lamminpää & Vesterinen, 2018), but utilizing it requires extra sensitivity. A friendly laugh with the students about a mistake is a way of letting them know it is not to be taken too seriously, whereas laughing at a student about their mistake is humiliating, disparaging, and malicious.

Alternatively, in some situations, the focus on correcting the cognitive side of the mistake could be shifted to correcting the attitude. If a student demonstrates negative emotional responses to mistakes and frames them as inherently negative themselves, one could guide the student to think of the mistakes as something positive, such as learning opportunities (Käfer et al., 2019). If the student seems to view the mistake as failure, they could be reminded of the broader learning goals that the mistake may even be advancing (Blumenfeld et al., 1991). However, using this approach, it is important for the students to still feel like their emotions are acknowledged and affirmed, and not just ignored and overlooked (Keen & Sevian, 2022). As a final example of emotional support, one could share their own or others' experiences of similar mistakes to demonstrate to the student that they are not alone and lessen the feelings of isolation (Käfer et al., 2019; Nunes et al., 2024; Simpson et al., 2025; Steuer et al., 2025; Wan et al., 2023).

Nevertheless, teacher support is not the only form of support available in most chemistry laboratory courses. The findings of Studies I and II suggest that peer support could be perceived as more neutral or even positive in mistake situations, supporting students' engagement and learning. Students should be encouraged to solve problems collaboratively, taking time to truly engage with the struggles. This is particularly important, as previous research has shown that students may not try to cognitively reason the observed deviations from their expectations (which might indicate that a mistake has occurred), but would, instead, call over the teacher or assume they were wrong in the first place (Keen & Sevian, 2022). On the other hand, prior research also suggests that teachers sometimes provide immediate support and resolve problems for students without encouraging them to critically think about the solutions, ultimately compromising their learning opportunities (Atabek-Yigit & Senoz, 2023a). In addition, it is known that peers may be more likely to provide one another with emotional support, maintaining the more positive affective landscapes of students (Keen & Sevian, 2022; Nunes et al., 2024), also promoting meaningful learning (Galloway et al., 2016).

Ultimately, the findings suggest that it is important to consider the type and cause of the mistake as well as the individual, as they play central roles in affecting the affective responses to mistakes. First, students seem to be more tolerant of experimental and careless mistakes, whereas conceptual mistakes and mistakes reflecting knowledge or skill gaps feel more burdensome. Therefore, the support provided to students should be tailored accordingly – at times, the challenges they face may be more significant, and the support should reflect this variability. Second, the findings of Study II reveal that students can react to mistakes in different ways based on their individual characteristics. Low performers reacted more negatively and more intensely to mistakes, similarly to students who associated high emotional costs with laboratory work in general. The latter group of students can be even more prone to excessive anxiety in the chemistry laboratory, as they not only experienced higher levels of trait-like anxiety but also expressed maladaptive responses to mistakes. Targeted, personalized support should thus be provided to students with these characteristics, and reminders that mistakes are not necessarily reflections of their skills and competencies but are unavoidable for all might be particularly beneficial for them (Tulis & Dresel, 2025).

Table 8. An overview of the recommended actions for educators to support students in productively dealing with mistakes.

Action	When
Frame mistakes positively	Before mistakes occur, e.g. at the beginning of the laboratory course
• Normalize mistakes and encourage students to make them as a part of the learning process • Illustrate how frequently mistakes can occur in the laboratory (based on the findings of this thesis, 29 % of all learning situations) • Indicate that mistakes provide learning opportunities • Use your professional knowledge of students' misconceptions to enhance learning • Do not evaluate students negatively based on their mistakes • Differentiate mistakes from failure in your speech	
Build a positive laboratory culture and the error climate	Before mistakes occur, but also in mistake situations
• Frame mistakes positively (see above) • Analyze the mistake with students • Emphasize what can be learned from the mistake • Provide students with instructional support • Encourage students to solve problems collaboratively • Provide students with affective scaffolding (see below)	
Affective scaffolding and emotional support	In mistake situations and moments of struggle
• Let the student know that you see how they are feeling and that their feelings are valid, normal and sensible • Cheer on students to continue, and let them know they are doing well • Approach the situation with humor, let the student know it is not to be taken too seriously • If the student is expressing negative attitudes towards mistakes, correct their attitude • Remind students of the broader learning goals, which the mistake may even be advancing • Share your own or others' experiences of similar mistakes • Do not laugh *at* students, do not allow any mocking, do not belittle or rush the situation	

5.4.3 Implications for teacher education

Based on the empirical findings, mistakes are an integral part of chemistry laboratory work, yet receiving teacher support in solving these mistakes was consistently associated with relatively intense, negative emotional experiences. This emphasises the need to address the phenomenon of navigating mistakes in teacher education, providing prospective teachers with a deeper understanding of how they could support their future students in navigating mistake situations, fostering persistence and promoting learning.

Simpson and colleagues' (2025) recent study represents reflective practices that could also be utilized in teacher education, guiding prospective teachers to reflect on their own experiences of failure and how they frame students' failure situations. Based on their findings, teachers initially framed the learning potential of failure as directly dependent on students' binary reactions – either the students persist, or they experience negative emotions and derail any learning potential. In light of the findings of this thesis, such framing seems rather distressing as students consistently associated negative affect with encountering mistakes. However, through engaging in a video-based reflection on how they as teachers navigated challenging failure situations in the classroom, they shifted their focus away from learner differences and external factors, and more to their self-failures as educators in supporting these students, which could foster professional growth and development (Simpson et al., 2025). Such reflections could also be extended to focus on how teachers articulate, describe and frame students' mistakes and their emotional responses to them.

Indeed, teachers' internalized framing of mistakes and failure can significantly impact the pedagogical practices they use and how they confront students who have made mistakes (Lutovac, 2019). Therefore, reflecting on these matters and initiating the processes of growth and professional development already at the teacher training phase would be highly relevant (Simpson et al., 2025). Moreover, the good practices for supporting students' learning from mistakes, presented in the section 5.4.2 above, could be introduced to prospective teachers as a part of these reflection activities. Finally, introducing prospective teachers to the ideas of what a central part of learning mistakes is, and how frequently they can indeed occur, could potentially further their own acceptance of mistakes (Lutovac, 2019; Nunes et al., 2024). This may also potentially foster positive development of their professional identity, viewing students' mistakes not as their own shortcomings or failure, but embracing them as important learning opportunities (see also Simpson et al., 2025).

5.5 Limitations and future directions

This thesis comes with some important limitations that should be acknowledged. In this section, these limitations are addressed along with providing directions for future research.

Probably the most significant limitation of the thesis relates to the representativeness of the sample. First, particularly in the laboratory, where students had multiple things to account for in addition to the data collection, the compliance rate of the EMA questionnaires was relatively low. Although the collected data consisted of responses that were missing completely at random, the low compliance rate may impact the results (also see Fritz et al., 2024). Students were more likely to respond to the EMA questionnaires at the beginning of the laboratory session, which may impair the generalizability of the results across the entire laboratory experience. It is also possible that students were more likely to choose not to respond to the questionnaire when they were feeling overwhelmed by the experiment, which could significantly undermine the representativeness of the results.

Second, the data were collected from only one laboratory course at one university in Finland. Within the data, a large majority of the participants identified themselves as females; however, it should be noted that this reflects the current gender distribution of students in the fields of natural sciences (Statistics Finland, 2024). Furthermore, the participants were mostly first-year university students, just starting to develop their professional science identities, which may influence how they view mistakes and respond to them (see e.g. Simpson & Maltese, 2017). To enhance the generalizability of the results, more versatile samples from different cultures, institutions, and across a broader age range and populations with a more even gender distribution are required. Nevertheless, a large majority of the students participating in the course agreed to participate in the research, and thus the data includes a moderate number of experiences from a relatively diverse group of students, suggesting decent representativeness.

Next, this data collection design primarily utilized single-item measures. When such indicators are used, the issue of internal consistency arises. While internal consistency cannot be measured for single-item indicators, other factors indicating measurement validity and reliability, such as the stability of the measure and cross-study consistency, can be assessed. In consideration of the items used in these three sub-studies, self-competence items (cf. skill) demonstrate good stability (Moneta et al., 2001), and the OLM items demonstrate significant cross-study consistency (Atabek-Yigit & Senoz, 2023a; B. Schneider et al., 2016; Upadyaya et al., 2021). Overall, previous research proposes that single-item measures can provide psychometrically sound alternatives to longer instruments in capturing affective-motivational constructs, especially when used in repeated measurement contexts, such as EMA designs (Fisher et al., 2016; Gogol et al., 2014; Hoeppner et al., 2011). Based on this notion and the findings of this thesis, the further use of these single-item indicators can be encouraged.

Due to the data collection design in Studies I and II, students also reported their lived affective experiences and whether they had made mistakes, which is both a strength and a limitation. In comparison to multiple other studies, this approach was less focused on affective experiences *caused by mistakes*, not portraying mistakes as the explicit object focus, nor positioning them at the centre of the affective experience. Thereby, the design did not guide students to reflect on their mistakes per se, but on broader, lived, affective experiences. This may result in noise caused by other factors, which is, in fact, always the case when collecting situational data in authentic contexts. Indeed, not all variables can – or even should – be identified, let alone controlled for. For example, social dynamics of the learning environment or the measurement time may influence the levels of students' affective experiences, inevitably impacting the results. However, such a design can arguably put the phenomenon in perspective, even providing a more realistic view with respect to situational and contextual factors.

Although mistakes and errors are treated as distinct concepts in this theoretical framing, it should be noted that the Finnish word "virhe" is used interchangeably both as "a mistake" and "an error". Therefore, as the questionnaires were implemented in Finnish, students' responses may also be related to errors. However, as was noted in Chapter Two, Theoretical framing, errors are essentially a subset of mistakes and thus should be inherently taken into consideration. Additionally, in Studies I and II, the definition of a mistake was left to students, but they were never asked what they understood by mistake (see also Käfer et al., 2019). Therefore, students were likely to report their mistakes based on a wide range of concepts and definitions. Despite these limitations, students emotionally respond to their subjective experiences (Pekrun, 2006), positioning their internalized concepts and definitions as crucial. Consequently, understanding emotional responses to subjective experiences of mistakes becomes primarily significant. Nonetheless, to gain a deeper understanding, future research should investigate students' definitions and conceptions of (laboratory) mistakes, plausibly in relation to similar concepts such as failures and errors.

Also related to the data collection design, the duration of affective states is not fixed, but instead, it may vary greatly (D'Mello & Graesser, 2011; Verduyn et al., 2009). Of all the measured affective experiences, boredom, for example, is a persistent state and thus, longer in duration (D'Mello & Graesser, 2011). These varying durations of the affective experiences set some limitations on the interpretation of the data. On the one hand, not all affective states may have been captured through the EMA design, whereas on the other, some emotions may have persisted for a longer time, reflecting triggers unrelated to the current measurement point.

Moreover, this data collection approach, relying on students' reporting, is also dependent on their recognition of their mistakes. It is therefore probable that the students may not have recognized all mistakes; prior research suggests that students may be better at identifying mistakes made by others than those of their own (Hämmerle et al., 2025) and that students with high levels of chemistry laboratory anxiety may be less adept at identifying procedural mistakes from a video (Atabek-Yigit & Senoz, 2023b). Nonetheless, the mistakes that remained unnoticed may also have been rather nonsignificant in shaping students' affective experiences (see Pekrun, 2006; Shuman & Scherer, 2013). What may be more important than students' recognition of mistakes here is their emergent emotional configurations.

These configurations could ultimately impact the reporting of data, for example, whether they choose to report not only their mistakes and seeking for support, but also their true affective experiences (Lanouette, 2024). Indeed, students may subscribe to alternative narratives of central matters, such as what counts as a mistake, what caused it, and how it should make them feel, portraying the quantitative data inherently as social texts, distinct from neutral, value-free or objective (Lanouette, 2024).

Thereby, even though this thesis consists of three sub-studies relying merely on quantitative data, it does not depict consistently just one story or narrative of mistakes (Lanouette, 2024). Regardless, approaching such a complex phenomenon with only quantitative data comes with significant limitations in terms of the depth of analysis. This inevitably results in averaging out the impacts of mistakes, positioning very different learning situations under the shared 'mistake situation' label. As such, the true diversity of the mistake situations remains unattainable in the analysis. However, to get at least a rough grasp on the diversity, students' affective responses were investigated with due respect to the mistake-situation factors. Furthermore, the findings of this thesis were discussed in relation to prior research addressing mistakes, errors, failures, struggles, and uncertainty that utilizes diverse methods, including multiple qualitative approaches. This body of research was drawn on to bring some of these plausible alternative narratives to the forefront (Lanouette, 2024), bringing more depth to the quantitative analyses. An example of this was highlighting the alternative interpretation of why students' negative affect may have been heightened in situations where they had received support from a teacher. Regardless, the data obviously still conceals numerous qualitative matters.

Therefore, it is advisable to approach this phenomenon with a versatile methodology in the future to gain deeper insights into the quality of students' affective responses to mistakes, in addition to the quantities focused on here. Additionally, the emotional trajectories in navigating such situations should be followed in more detail. To achieve these goals, future research could entail, for example, interviews, videos, observation, and diary reflections. Quantitative data could also provide further insights and even some qualitatively distinct configurations into the phenomenon by approaching mistake situations through, for example, the latent profile analysis framework (see Reindl et al., 2020).

Furthermore, this study could only focus on a limited number of affective constructs. This was primarily to keep the length of the EMA questionnaires as manageable, reducing the response burden for participants, but also due to the limitations of the analytical approaches. Indeed, to maintain the complexity of the statistical models at a low enough level, only a limited number of outcomes can be included. Therefore, to capture a wider range of affective outcomes of mistakes, future research should focus on other affective constructs.

In the same manner, controlling for additional, more stable individual-level variables, such as students' discipline-based interest (Renninger & Hidi, 2019), motivational orientations (Henry et al., 2019), or general error beliefs (Tulis et al., 2018), may provide new insights into the phenomenon. For example, Tulis and colleagues (2018) suggest that students who subscribe to more positive beliefs about mistakes are more likely to report more adaptive reactions to them. Thus, future research should aim to identify the role of such factors in predicting students' situational affective responses and their probabilities of making mistakes.

Next, the distinctions between the EMA questionnaires related to pre-lab mistakes and the laboratories in terms of whether students may have been aware of their mistakes need to be addressed as limitations. Because students self-reported their mistake experiences in the EMA questionnaires during laboratory sessions (Studies I and II), they also needed to be aware of them, whereas in the pre-labs (Study III), students' mistakes were identified based on their exercise scores, and they only received feedback on whether they had made a mistake after completing the EMA questionnaire. Thus, they may not have realized that they had made a mistake, which could significantly influence their affective states. Moreover, pre-labs were conducted individually, whereas the laboratory experiments were performed in pairs, possibly also impacting the results. Therefore, it must be noted that mistakes across these different learning contexts, and thus the results of the sub-studies I/II and III, are not entirely comparable.

Finally, beyond those that would help address the limitations and shortcomings of this study, other directions for future research on the topic also emerged. Future research could examine, for example, how the perceived error climate of the laboratory environment influences students' responses to mistakes, how students' situational responses to mistakes relate to their beliefs about their adaptive handling of mistakes, and how students' responses to mistakes shape their stable experiences (such as trait-like motivation and error beliefs) as well as their learning outcomes. In addition, there is a need for more knowledge on teachers' perceptions of mistake situations and how they handle them. Future research might also focus on if and how these are different when dealing with the more inherently negative failure, and what kind of role students' learning goals play in determining their perceptions of failure. Overall, there is still considerably little research on how to productively deal with mistakes, especially within science education contexts. While this thesis opened the discussion and contributed insights through three sub-studies and this dissertation as a whole, this field of research is still emerging, leaving ample room for future investigations.

6 Conclusions

The main aim of the research presented in this thesis was to investigate students' affective responses to mistakes in an undergraduate chemistry laboratory course. A person-in-context approach (Sinatra et al., 2015) was adopted, positioning students as individuals in an authentic learning context. Students' affective experiences and responses to mistakes, fluctuating over time, were examined across multiple learning situations using an EMA design, and the roles of individual, situational, and contextual factors in shaping this phenomenon were focused on (Pekrun, 2006; 2024).

First, mistakes appeared as an inseparable part of the laboratory course. Students reported making mistakes in almost one-third of all learning situations captured in the laboratory sessions, and pre-lab mistakes were identified as frequently as in almost two-thirds of the learning situations. Being so common, students should feel comfortable navigating mistake situations. Nonetheless, the findings reveal that mistakes are, on average, associated with higher levels of challenges and negative, activating emotions, as well as lower levels of perceived competence and positive, deactivating emotions – indicating that this may not be the current situation.

However, although the effects appear rather negative, the observed increase in emotional activation and challenge could facilitate engagement and ultimately, learning. Furthermore, not all mistakes were perceived as equally negative. Experimental and careless mistakes were more neutral in terms of the related affective states, whereas students' negative responses were even more intense when the mistake was conceptual or caused by a skill or knowledge gap. The form of support in resolving the mistake appears to matter; peer support seemed more neutral, whereas teacher support was linked to an intensified negative effect. Moreover, mistakes during pre-labs were not linked to the levels of students' interest, whereas students were less interested when they had made mistakes in the laboratory. There were also differences across students; high-performing students remained more relaxed and became less anxious and frustrated in the moments of mistakes, whereas students with high emotional costs associated with laboratory work experienced an intense increase in anxiety when they made mistakes. On a positive note, students might emotionally overcome their mistakes in a relatively short time.

Based on the findings, although students felt less competent and more challenged in the pre-lab activities when they had made a mistake, the mistake no longer influenced students' engagement or any of its elements in the subsequent laboratory session.

These findings add to the discourse on the reform of chemistry laboratory education, framing mistakes and learning to navigate such scientific challenges as a central matter. They underline the situational nature of students' affective experiences and responses to mistakes, encouraging future research to explore the matter with due respect to the situational variation in authentic environments. By bridging several fields of research together, the thesis demonstrates significant potential in employing methodologies rooted in educational psychology in the context of chemistry and science education. Additionally, the findings advocate a need for affective scaffolding to support students in navigating mistakes, and the results show that educators should indeed pay significantly more attention to this. This affective scaffolding should be targeted at certain groups of students, particularly low-performers and students with high emotional costs, struggling with negative affect toward making mistakes. The thesis provides educators with some concrete actions that could be undertaken to foster affective learning and support students navigating mistake situations; students' emotional responses should be acknowledged and affirmed, resolving mistakes with peers should be encouraged, and mistakes should be normalized by, for example, highlighting their high frequency with explicit numbers or sharing one's own mistake experiences.

Finally, the thesis began with the question: Without mistakes, can genuine learning occur? As these are the concluding remarks, it appears that the question remained unanswered. Indeed, the thesis was focused on students' affective responses to mistakes and did not measure changes in their behavior or knowledge, that is, learning. Thus, another question arises: Is this a failure? In this thesis, failure was defined as a discrepancy between the aim and the outcome. While the opening question was left open for future investigations, it was presented as food for thought or a premise, emphasizing the crucial importance of understanding mistakes, and the thesis was, after all, successful in relation to its aims. Therefore, by definition, this is not. Nonetheless, the narrative may have deviated from the expected trajectory, so perhaps there was a mistake. How curious.

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