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How making mistakes shapes students' situational engagement in chemistry laboratory?

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ABSTRACT
This study aims to identify the relationship between mistake situations and students' situational engagement. The data were gathered from 155 undergraduate students in a chemistry laboratory course using the ecological momentary assessment. Mistakes and the elements of engagement were recorded on-task. The effect of mistakes was examined using multilevel structural equation modelling, considering that situational responses are nested within individuals, enabling us to consider how the characteristics of individuals and learning situations appear in relation to mistakes. Our results suggest that learning situations integrating theory and practice predict high situational engagement. In these situations, students were also more likely to commit mistakes. Making mistakes affected the elements of engagement. Computational mistakes intensified the negative effect on interest, and skill, and the positive effect on challenge, while practical mistakes reduced these effects. Seeking support after making mistakes was associated with high levels of challenge, and teacher support was associated with lower skill levels. Based on the results, students' situational engagement during laboratory courses can be supported by strengthening the connections between theory and practical activities and by encouraging students to solve arising problems collaboratively.

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Introduction

A chemist might describe mistakes as a catalyst for discovery. Yet in the field of science education research, it remains unclear what other products they may catalyse. This research provides insight into how making mistakes and other characteristics of learning situations affect undergraduate students' engagement in the chemistry laboratory on a momentary level.

In this study, we approach mistakes as situation-specific instances that affect situational engagement and investigate them on-task. Accordingly, we used situational engagement as the theoretical lens because it enables us to analyse the short-term

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effects of making mistakes during laboratory instruction. In their review article, Agustian (2022) argued, that the research on chemistry laboratory education should not only focus on the learning outcomes, but also on learning processes, and the learning of sciences, which making mistakes is an intrinsic part of.

Although being engaged and learning are not equivalent, engagement can indirectly affect learning. Engagement has an impact on the learning strategies that students use (Schmidt et al., 2018), the levels of self-regulation that they demonstrate (e.g. Lee et al., 2014), and their academic achievement. On the other hand, the level of engagement students experience depends on the activity and the studied context (Inkinen et al., 2019; Renninger & Su, 2012).

There are various constructs of learning engagement. It can be categorised as general or learning situation-specific engagement (e.g. Salmela-Aro et al., 2016), and the latter is the applied approach in this study. We utilised the optimal learning moment (OLM) theory to measure the situational engagement of students (Schneider et al., 2016). According to this conceptualisation, instances, where students experience high levels of interest, skill, and challenge simultaneously, indicate that an OLM is present. Frequent experiences of high situational engagement, i.e. OLMs, can increase the longitudinal motivation of students (Hidi & Renninger, 2006), and promote students' absorption of fundamental knowledge (Tuominen-Soini & Salmela-Aro, 2014).

The theory of OLMs, derived from flow theory, contains the idea of uninterrupted workflow. Making mistakes might disturb this flow, possibly resulting in a change in the level of engagement. However, there is very little research on the on-task effects of making mistakes. Previous studies show, that making mistakes induces different self-regulatory processes in students, adaptive or maladaptive. These processes depend on, for instance, students' attitudes toward mistakes and their goal orientation, as well as error climate in the learning environment (Tulis et al., 2016; Soncini et al., 2022).

Based on previous research, there are connections between students' learning engagement and self-regulation (Lee et al., 2014), as well as students' adaptive reactions to mistakes and self-regulation (Tulis et al., 2016). Mistakes and engagement could be linked in this regard, with self-regulatory processes mediating the effects. This article aims to identify the relationship between mistake situations and situational engagement.

The data of this research has been collected using the ecological momentary assessment (EMA), measuring the on-task experiences of students in the chemistry laboratory. In four laboratory sessions, students responded to three or four EMA questionnaires containing items on optimal learning elements (interest, skill, and challenge) and making mistakes. The background of the plausible mistake was recognised using a set of claims in the questionnaires. We used multilevel structural equation modelling (MSEM) to form the models describing the interactions between situational background variables, such as making mistakes and combining theory and practice, along with the individual background variables, such as student's performance and major, on OLMs and its elements. Finally, we aimed to discover how making mistakes, and more specifically different types of mistakes, affect the situational engagement of undergraduate students.

Learning in the chemistry laboratory

Laboratory teaching is an ever-present part of chemistry education. Its importance, despite its distinctive nature, has been questioned regularly (e.g. Bretz, 2019; Hofstein

& Lunetta, 2004; Kirschner, 1992), but there is also research providing justification for it (Seery et al., 2024; Agustian, 2022). In a recent review of the learning outcomes of undergraduate chemistry laboratories, Agustian (2022) predicated experimental competencies, disciplinary learning, higher-order thinking skills and epistemic learning, transversal competencies, and the affective domain as significant accomplishments of laboratory education. Most of the significant learning outcomes result from the distinctive learning environment of laboratories, which differs greatly from classrooms and lecture halls (Seery, 2020; Kirschner, 1992).

Chemistry laboratories have been established as a place for *learning to do science* (Seery, 2020; Agustian, 2022). This means that students learn to use their scientific knowledge to, for example, carry out experiments, interpret data, and draw conclusions, acquire skills and competencies that scientists need. Accordingly, one of the learning goals of laboratory education should be learning to make mistakes and encounter failures, as it is an intrinsic part of doing science. Regardless, previous research has implied, that students typically try to avoid mistakes and negative affective experiences it evokes in the laboratory (Galloway et al., 2016; DeKorver & Towns, 2015). This aligns with the notion, that the affective domain of laboratory education remains often overlooked by the students, teachers, and curriculum developers (Galloway et al., 2016; Seery et al., 2019; Agustian, 2022).

Situational engagement

Learning is a complex process, and one way to consider the complexity of it is by identifying the varying learning situations. Learning is linked to and can be researched through the lens of student engagement (Carini et al., 2006; Schneider et al., 2016), with its contemporary emphasis on the situational approach (Salmela-Aro et al., 2016; Schneider et al., 2016; Schmidt et al., 2018; Salmela-Aro et al., 2021). In science, the learning process is rarely linear but instead consists of insightful moments, even epiphanies. In these moments, students must be receptive to learning and there are strong indications, that students are highly situationally engaged (Schneider et al., 2016).

In this paper, engagement is studied using Schneider et al.'s (2016) conceptualisation of situational engagement. It is based on the flow theory (Csikszentmihalyi, 2000; Schmidt, 2010), and situational interest (Krapp & Prenzel, 2011), emphasising the domain-specific nature of engagement in duration and intensity. It defines high situational engagement as instances, where students are simultaneously highly interested in, skilled at, and challenged by the activity they are engaged in. These instances are referred to as optimal learning moments (OLM).

The conceptualisation of Schneider et al. (2016) combines positive and negative psychology, stating that in addition to being interested and skilled, learning also requires challenge and therefore demands work and even failures. Tasks and activities must be sufficiently challenging, and a moderate amount of stress and even anxiety pertain to the learning process (Tuominen-Soini & Salmela-Aro, 2014; Schneider et al., 2016; Vilhunen et al., 2022).

Engagement is typically characterised as an affective construct. However, the elements of optimal learning can be separated into different learning domains. Thus, situational engagement can be interpreted as overlapping with cognitive engagement (see Agustian, 2022), particularly in terms of the demand for sufficiently high challenges, but with a shorter duration. Concurrently, it can be connected to an affective domain through interest and skill experiences (Agustian, 2019; Galloway et al., 2016). Additionally, laboratory work rather automatically activates the psychomotor domain, and thus, experiences of high situational engagement in the chemistry laboratory could also enable meaningful learning that combines thinking, feeling, and acting (cf. Galloway et al., 2016; Novak, 2010).

Despite the short-term duration of the construction, frequent experiences of high situational engagement can improve students' longitudinal motivation and schoolwork engagement (Hidi & Renninger, 2006). Situational engagement results from an interaction between a student and the environment, depending on the context and the ongoing activity (Renninger & Su, 2012; Inkinen et al., 2019). Interestingly, the dependence between OLMs and students' backgrounds, i.e. academic achievement, learning skills, and schoolwork engagement (Pöysä et al., 2020), in addition to gender in Finnish schools (Schneider et al., 2016), has not been distinctively established, unlike longitudinal motivation, interest, and engagement (e.g. Hidi & Renninger, 2006; Schnitzler et al., 2021).

In line with the expectancy-value theory, students' perceptions of the utility and importance of the learning situation are reflected in their situational engagement (Eccles & Wigfield, 2020; Salmela-Aro et al., 2021; Upadyaya et al., 2021). Nevertheless, interventions, where students are encouraged to meet challenges, diminish the effect of these student attainment and utility values (Upadyaya et al., 2021).

Situational engagement in chemistry laboratory

As OLMs are situation-specific, different activities have varying abilities to stimulate students' situational engagement. Inkinen et al. (2019) studied the occurrence of OLMs during a set of different classroom activities in secondary-level science education in Finland and the USA. In Finland, 20.7%, and in the USA, 15.1% of the time spent on laboratory work, students were situationally engaged. In both countries, the average level of experienced challenge during lab work was one of the lowest among all activity types. Overall, the average challenge levels were lower than skill and interest levels in all activity types.

According to the empirical findings of Galloway et al. (2016), some students recognise that being challenged in the undergraduate chemistry laboratory will motivate them to work hard, and therefore increase their level of engagement. The researchers also described that some students, on the other hand, experience overwhelming challenges, and as a result, a decrease in their motivation. This aligns with the conceptualisation of optimal learning theory, stating that the tasks must be challenging enough, but not too difficult to avoid the decrease in students' experiences of skill.

Atabek-Yigit and Senoz (2023) explored OLMs in a similar setting to this research, in an undergraduate chemistry laboratory. In their study, only 2.5% of the responses indicated OLMs. Their results align with Inkinen et al. (2019), stating directly, that low challenge levels were the barrier to obtaining OLMs. Despite their infrequent occurrence of OLMs, they found a positive correlation between connecting theory to the ongoing lab work and OLMs. They also identified positive correlations between OLMs, and getting good grades, as well as OLMs, and experiencing the work being beneficial for students' prospective careers.

There are multiple aspects to laboratory sessions, as they often contain purely practical phases as well as phases combining theory and practice, in which students do calculations and analyse the results. According to the results of Vilhunen et al. (2021), students' epistemic emotions vary in these different aspects, with higher levels of anxiety, confusion, and frustration experienced during computational parts of laboratory work, suggesting higher cognitive demands. Thus, situational engagement in the laboratory should be investigated with due respect to these aspects, and not as a whole.

Mistakes as a part of learning

In recent years, constructive and sociocultural learning approaches have been prevalent in the field of education. These approaches construe that students are active agents, learning occurs through an interaction with the environment and learning situation, and that knowledge is built upon knowledge (Piaget, 1964; Leach & Scott, 2003). The nature of science, especially in chemistry, aligns with this contemporary view of learning, as scientific theories and concepts are oftentimes constructed through trial and error. Accordingly, making mistakes, and experiencing failure are inevitable parts of learning (cf. Allchin, 2012). Nonetheless, the following interaction of making a mistake within a person and with the learning situation is a relatively under-researched topic.

As Agustian and Seery (2017) studied the role of pre-laboratory activities in undergraduate chemistry laboratory education, they noticed, that preparatory exercises tended to result in fewer experimental mistakes made by the students in the laboratory. Especially, if the preparative learning exercises were interactive and contained videos, students made significantly fewer mistakes compared to only being given written material beforehand. This might evoke deeper thinking in the laboratory and reduce the cognitive load to a sufficient level.

Mistakes students encounter in a chemistry laboratory can be carelessness errors or mistakes caused by a lack of skill, knowledge, or understanding. The latter can lead to a conceptual conflict and further conceptual change in students' thinking (see D'Mello et al., 2014; Merenluoto & Lehtinen, 2004; Chiu et al., 2019). Conceptual conflicts typically induce negative emotions, although positive emotions are generally associated with the learning process as a whole (Chiu et al., 2019). Tulis and Fulmer (2013) also proposed that staying engaged while facing mistakes may not depend on students' maintained positive affect. Another way to categorise mistakes in the chemistry laboratory is to divide them into practical and theoretical ones. Practical mistakes fall under the psychomotor domain, while theoretical mistakes belong to the cognitive domain.

Previously, students' beliefs about making mistakes or encountering failure have been studied in contrast to their academic performance, goal orientation, and teacher's ways of handling mistakes (see Huangfu et al., 2023; Käfer et al., 2019; Leighton et al., 2018; Tulis, 2013; Tulis & Fulmer, 2013; Soncini et al., 2022). Additionally, students' adaptive reactions after making mistakes have been studied in contrast to teacher's reactions, error climate in the classroom, and goal orientation (see Käfer et al., 2019; Soncini et al., 2022; Tulis & Ainley, 2011; Tulis et al., 2018). The studies suggest that mastery goal orientation and support given by teachers are significant predictors of positive beliefs and adaptive reactions toward mistakes. These factors are proposed to enhance learning (Huangfu et al., 2023; Tulis et al., 2018). Peer interaction and humour can be used to regulate negative emotions stemming from mistakes and failures during laboratory tasks (Lamminpää & Vesterinen, 2018).

If students make mistakes in the chemistry laboratory, it forces them to decide on the course of action to overcome the challenge. Therefore, it brings control to the students from the laboratory manual, making the students active agents in the learning process. Being able to handle the situation can evoke confidence in the students, and it might even promote meaningful learning (cf. Galloway et al., 2016; Seery et al., 2019).

Learning could also be supported with error management treatment, where students are actively encouraged to make mistakes in the learning process (Keith & Frese, 2008). This promotes a positive error climate, enhancing students' adaptive reactions and positive attitudes toward making mistakes (Kuhl, 2000; Soncini et al., 2022). The error management treatment appears effective in long-term learning, while students' performance within a session may be unoptimised (Keith & Frese, 2008). Käfer et al. (2019) described that teachers who promote a positive error climate use their professional knowledge of students' misconceptions to enhance students' learning processes and they do not negatively evaluate students based on their mistakes. Instead, the learning potential stemming from mistakes is actively embraced. This aligns with research on productive failure, noting that in order to deal with mistakes productively, a subsequent instructional activity should follow (cf. Loibl & Leuders, 2019; Kapur & Bielaczyc, 2012).

It is still unclear, how making mistakes relates to students' engagement, but Keith and Frese (2008) predicated, that it disturbs the workflow. Hence, considering optimal learning theory (Schneider et al., 2016) it might further decrease the level of engagement. However, students who demonstrate adaptive self-regulation, cognitive, and affective reactions following mistakes are more likely to stay engaged subsequently (Kuhl, 2000; Käfer et al., 2019; Tulis et al., 2016; Soncini et al., 2022). The same students are also more likely to analyse the mistake deeply and consequently learn more effectively (Käfer et al., 2019; Tulis et al., 2016).

Despite the consensus on the importance of mistakes among education professionals, not all students view mistakes as a natural part of learning (Leighton et al., 2018). DeKorver and Towns (2015) studied chemistry students' learning goals in an undergraduate chemistry laboratory course, and their results indicated, that most of the students identified avoiding mistakes and getting the right answer as an important goal. Making mistakes was associated with negative emotions and it undermined students' self-image. Students' expectations have been found to significantly frame their actual experiences in the chemistry laboratory (Galloway & Bretz, 2015a), which underlines the requisite of a positive error climate and teachers' support after making mistakes in the laboratory. Students should be encouraged to see mistakes as learning opportunities instead of roadblocks on their way to finishing the work.

Finally, promoting a positive error climate through error management treatment in the chemistry laboratory should be done at the beginning of the laboratory sessions. After mistakes already have occurred, students are naturally more vulnerable, and teachers should avoid contemplating mistakes as a valuable learning opportunity on a general level. Instead, for example, emphasising the benefit of discussing the idea the student proposed is a good policy (Wan et al., 2023).

The present study

To date, there is very little research on the on-task effects of making mistakes as a part of learning. However, in their previous studies, Tulis and colleagues (2018, 2016) have proposed, that the effect of making mistakes is connected to the specific error situation, beyond variables like school subject, error climate, and goal orientations, and that it should be studied on-task. In this research, we focus on this situation-specific aspect of mistakes that students commit in the chemistry laboratory. The ecological momentary assessment was used to provide on-task data on students' engagement and the occurrence of mistakes. We study students' situational engagement through the lens of optimal learning moments and elements of optimal learning.

The specific research questions in this study 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?

Method

This research was conducted at a Finnish university, and the data were collected during the autumn of 2023. Ecological momentary assessment (EMA) questionnaires were used to collect the data during four laboratory sessions at the undergraduate students' first chemistry laboratory course.

Research environment and participants

The data collection took place in undergraduate students' first chemistry laboratory course, which is mandatory for chemistry, biochemistry, and biotechnology majors as well as all students studying chemistry as a minor. The course consisted of seven practical laboratory works that were: 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, 7. Buffer solutions. Before each 3- to 4-hour laboratory session, students were to complete mandatory learning exercises on an online learning platform to prepare for the upcoming session.

The experiments were traditional undergraduate laboratory tasks. The course's learning goals were to be able to perform laboratory work safely under instruction and to master some classic chemical analysis and separation methods. Weekly experiments were conducted at a teaching laboratory with one teacher per 16 students. There were multiple teachers at the course, but all 16-student-groups had the same teacher each week, and there were no teaching assistants. Students carried out the experiments in pairs, working with the same person throughout the entire course.

A total of 178 students enrolled in the course, and 155 of them voluntarily participated in the research. Each participant completed a background questionnaire online. Among the participants, 115 (74.2%) identified themselves as female and 36 (23.2%) as male. The majority, namely 124 (80.0%) of the participants were first-year university students, while 18 (11.3%) were second-year students, and the rest, 13, were third-year or higher. The study majors of the participants were distributed as follows: 47 (30.3%) chemistry, 43 (27.7%) biochemistry, 35 (22.6%) biotechnology, 8 (5.2%) physics, 7 (4.5%) biology, 6 (3.9%) mathematics, and 9 (5.8%) something else.

Data collection

Students had completed the first three laboratory experiments before the data collection began. Our data collection spanned the last four subsequent laboratory sessions (liquid–liquid extraction, pH-titration, complexometric titration, and buffer solutions). Participants responded to a total of 13 EMA questionnaires during the laboratory sessions and altogether we got 1049 situational responses. The compliance rate was 52.1%.

We used EMA questionnaires to measure the elements of OLMs and to detect the mistakes that students noticed they had made in the laboratory. EMA questionnaires were an eligible choice due to their effectiveness in gathering highly situational and subjective experiences (Carson et al., 2010; Hektner et al., 2007; Salmela-Aro et al., 2016). Additionally, the situational self-report setting significantly reduces recall bias in the responses (Mulligan et al., 2005; Kitterød & Lyngstad, 2005; Salmela-Aro et al., 2016). Responding to the questionnaires only took from one to five minutes at a time, and thus the respondent burden remained moderate in this research.

In the laboratory setting, links to the EMA questionnaires were embedded in the practical work instructions. Students were instructed to answer the questionnaires on their phones at specific points during the practical work, with 3–4 EMA surveys implemented in each laboratory session. The teaching laboratory at the university generally allows phones, so this is in line with standard practice. As the EMA questionnaires were synchronised with the student's progress, they did not disrupt the workflow and unintentionally affect engagement. Questionnaires took place after finishing a section of the work, and the last questionnaire was responded to at the end of the laboratory session before discussing the work with the teacher.

As students' situational engagement was investigated through the optimal learning elements, we specifically measured the level of students' interest, skill, and challenge. The questionnaire phrasing, that we used, aligned with Inkinen et al. (2019), with participants reporting their level of agreement on the following questions: '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?'. Participants answered on a 5-point Likert scale with response categories from '1 = Not at all.' to '5 = Very much.'

Concerning laboratory work, we focused on the mistakes the students committed. Therefore, the EMA questionnaires were used to detect the mistakes and the background of each mistake with a set of claims. First, students were asked whether they noticed making a mistake in their previous activities, and if so, they were instructed to select the applicable claims. The claims included were 'The mistake regarded practical working.' that we named as *Mistake, practical*, 'The mistake regarded analysis or calculations.' i.e. *Mistake, computational*, 'Teacher helped me to solve the error.' i.e. *Mistake, teacher helped*, 'My peers helped me to solve the error.' i.e. *Mistake, peers helped*.

Analytical approach

The theory of OLMs, defined as instances characterised by high situational engagement, posits that when students simultaneously experience high levels of interest, skill, and challenge, an OLM is present (Schneider et al., 2016). In this study, we established the average value of each variable – interest, skill, and challenge – as the threshold for optimal learning. We opted for these threshold values, as the theory behind situational engagement (Schneider et al., 2016) states, that to obtain an OLM, the interest, skill, and challenge levels must all reach sufficiently high values. The average values for interest, skill, and challenge were 3.67, 3.55, and 2.47, respectively. Therefore, we coded instances, where participants reported interest and skill levels of above 4, along with challenge levels above 3 concurrently, as indicative of an OLM.

Like the OLMs, the event of a mistake and the explanatory claims concerning making the mistakes were coded as categorical variables. Based on the instructions of the experiment, a categorical variable on whether the phase of the activity required combining theory with practice was created. Such phases required the students to, for example, calculate something, make inferences based on observations, or analyse the results.

Six categories describing performance on learning assignments were created based on the total points students earned from the online learning assignments before laboratory sessions. We used these categories as an observed background variable, interpretive of their theoretical understanding of the concepts of chemistry central for the laboratory assignments. Students who scored less than a third (33.3%) of the points were graded 0, less than 46.6% were graded 1, less than 60.0% were graded 2, less than 73.2% were graded 3, less than 86.6% were graded 4, and above 86.7% were graded 5 (Table 1). Other background variables used for the analysis were gender and whether chemistry was student’s major or minor.

For the analysis, we used multilevel structural equation modelling (MSEM) framework, as it can account for the hierarchical structure of the data. The analyses were conducted using Mplus 8.6 (Muthén & Muthén, 1998-2017). The situational responses were nested within individuals, and therefore the latter were treated as clusters. The effect of gender, major, and performance on learning assignments were measured at the individual (between) level, whereas the student reported mistakes, explanatory claims concerning making the mistakes, and moments combining theory with practice were considered predictors on the momentary (within) level. At within level our sample size was 1049, and at between level the sample size was 155, which is adequate for conducting MSEM analyses (cf. Hox & Maas, 2001).

Table 1. The distribution of the grade categories.

Grade	Frequency	%
0	3	1.9
1	4	2.6
2	13	8.4
3	47	30.3
4	66	42.6
5	22	14.2

Results

The first subsection describes the model fits, and the following two subsections present the analyses of how individual and momentary characteristics affect students' situational engagement measured by OLMs. These analyses aim to answer research questions 1 and 2. The final subsection focuses on the effects of different types of mistakes, as well as the form of support used in solving the mistakes, aiming to answer research question 3.

Model fit

Four models were created to answer all three research questions. Two models were two-levelled, combining the individual and momentary characteristics, and the other two were single-levelled, looking more closely at the effect of mistake types and forms of support on students' situational engagement. As some of the variables were not normally distributed, in the two-level models, we used the weighted least square mean and variance adjusted (WLSMV) estimator, and in single-level models, the maximum likelihood for robust standard errors (MLR) estimator was applied (see Muthén, 1994). Each model's fit was evaluated using several fit indices. Based on the summary of previous research (Schreiber et al., 2006), the ranges of acceptable scores were: $< .06$ for Root Mean Square Error of Approximation (RMSEA), $> .95$ for Comparative Fit Index (CFI), and $< .08$ for Standard Root Mean Square Residual (SRMR).

We analysed the effects of both individual and situational level variables on optimal learning in the first model. Two-levelled approach was adopted due to intraclass correlation coefficient (ICC) being.102 for making mistakes and .392 for OLMs. Multi-level approach is suggested when ICCs are greater than .100 (Irimata & Wilson, 2018). To evaluate the model fit for the first MSEM analysis we used five fit indices that Mplus provides (RMSEA = 0.017; CFI = 0.993; TLI = 0.894; SRMR = 0.000 (within), SRMR = 0.075 (between); $\chi^2 = 1.295$ ($p = 0.2552$)).

The second model was used to identify the effects of individual and situational level variables on the optimal learning elements. ICCs were .102 for making mistakes, .438 for interest, .244 for skill, and .191 for challenge, indicating that two-levelled approach was adequate. The same fit indices were used (RMSEA = 0.000; CFI = 1.000; TLI = 1.000; SRMR = 0.000 (within), SRMR = 0.033 (between); $\chi^2 = 0.778$ ($p = 0.8546$)), and they indicated a perfect model fit.

The third and fourth models focused on the explanatory mistake claims, using the type of the mistake (i.e. was the error practical or computational) and the form of support used in solving the mistake (i.e. support from teacher or from other students) as moderators on the effect of making a mistake. As the number of situations in which these explanatory mistake claims were given was considerably lower than the number of predictor variables used on two-level models, these analyses were made only on a situational level. As all variables were categorical, logistic regression model was used to measure the effect of the explanatory mistake claims on the probability of OLMs. In the fourth model, the explanatory mistake claims were used as predictors for student reported levels of skill, challenge and interest analysis in a linear regression model. As these models did not include any latent variables and the residuals were allowed to covariate freely, the fit indices resulted in perfect fit (RMSEA = 0.000; CFI = 1.000; TLI = 1.000; SRMR = 0.000).

Individual and momentary characteristics on optimal learning moments

Out of all measured learning situations (N = 1049), 125 (11.9%) were OLMs. There were 423 (40.3%) learning situations, where students were to combine theory and practice, and 304 (29.0%) where students reported having made mistakes. Figure 1 presents the first two-level MSEM model, that describes the effects of both individual and momentary level variables on OLMs.

On an individual level (see Table 2), students' gender, major, and performance on learning assignments did not predict the probability of OLMs on a statistically significant level. However, based on this level of analysis, the students with higher performance on learning assignments were significantly less likely to make mistakes.

On a momentary level (see Table 3), the phase of laboratory work combining theory and practice was a significant predictor of OLMs. Based on the model, making a mistake or the laboratory session did not have a significant effect on the probability of OLM. However, students were significantly more likely to report mistakes during pH titration (laboratory session 2), as well as during phases of work combining theory and practice.

Individual and momentary characteristics on elements of optimal learning

Further analysis on the elements of OLMs is presented in Figure 2. This analysis described the effect of momentary and individual level predictors on students' self-reported levels of interest, skill, and challenge.

On an individual level (see Table 4), higher performance on learning assignments was the only significant predictor of students' experiences of interest, skill, and challenge.

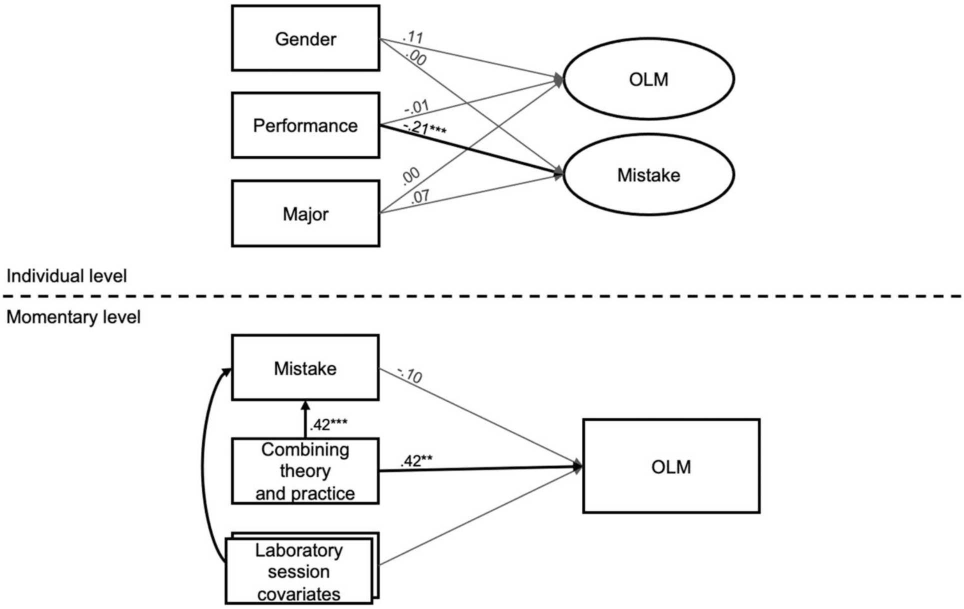

Figure 1. A two-level model that describes the effects of making mistakes on optimal learning moments, significant at * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$ levels. The values for laboratory session covariates are presented in Table 3.

Table 2. The results of the multilevel structural equation model on the effects of gender, performance on learning assignments and major on optimal learning moments and the probability of making mistakes on the individual (between) level.

	Optimal learning moment			Making a mistake		
	β	S.E.	*p*	β	S.E.	*p*
Gender	.11	.25	.67	.00	.12	.97
Performance	−.01	.10	.92	−.21	.05	<.001
Major	.00	.29	.99	.07	.11	.51

Notes: Presented estimate values (β), standard errors (S.E.) and *p*-values (*p*).

Table 3. The results of the multilevel structural equation model on the effects of making a mistake, combining theory and practice, and laboratory sessions on optimal learning moments on the situational (within) level.

	Optimal learning moment			Making a mistake		
	β	S.E.	*p*	β	S.E.	*p*
Making a mistake	−.10	.07	.14	–	–	–
Combining theory and practice	.42	.14	.003	.42	.10	<.001
Reference: Liquid-liquid extraction						
pH-titration	−.34	.18	.06	.47	.13	<.001
Complexometric titration	−.03	.19	.86	−.05	.14	.74
Buffer solutions	.04	.14	.77	−.09	.12	.49
Reference: pH-titration						
Complexometric titration	−.06	.03	.10	−.51	.13	<.001
Buffer solutions	−.05	.03	.08	−.55	.13	<.001
Reference: Complexometric titration						
Buffer solutions	.01	0.03	0.77	.04	.14	.77

Students with high performance on pre-session online learning assignments were more likely to experience high levels of interest and skill, and less likely to experience high levels of challenge.

On a momentary level (see Table 5), combining theory with practice predicted lower interest and skill, and higher challenge. The observed effect of the mistakes was codirectional with the aforementioned.

Types of mistakes and forms of support on situational engagement

To answer, how the type of mistake made, and the form of support used in solving the mistake affected situational engagement, the situations with mistakes were further analysed on a momentary level. Out of the total of 304 mistakes, students reported making 127 practical and 132 computational mistakes. Teacher support was sought in 93 situations and support from peers in 67 situations.

The type of mistake or the form of support used when solving the error did not have statistically significant effects on the frequency of OLMs (see Table 6). However, they had an effect on the elements of optimal learning (see Table 7). Students experienced level of interest and skill were higher, and the experienced level of challenge was lower when mistakes were practical. The effect of the computational mistakes was the other way around, as students perceived those situations as more challenging and felt less skilled. Both seeking support from teachers as well as seeking support from peers predicted higher levels of challenge, but, out of these two, only seeking support from teachers predicted significantly lower experienced levels of skill.

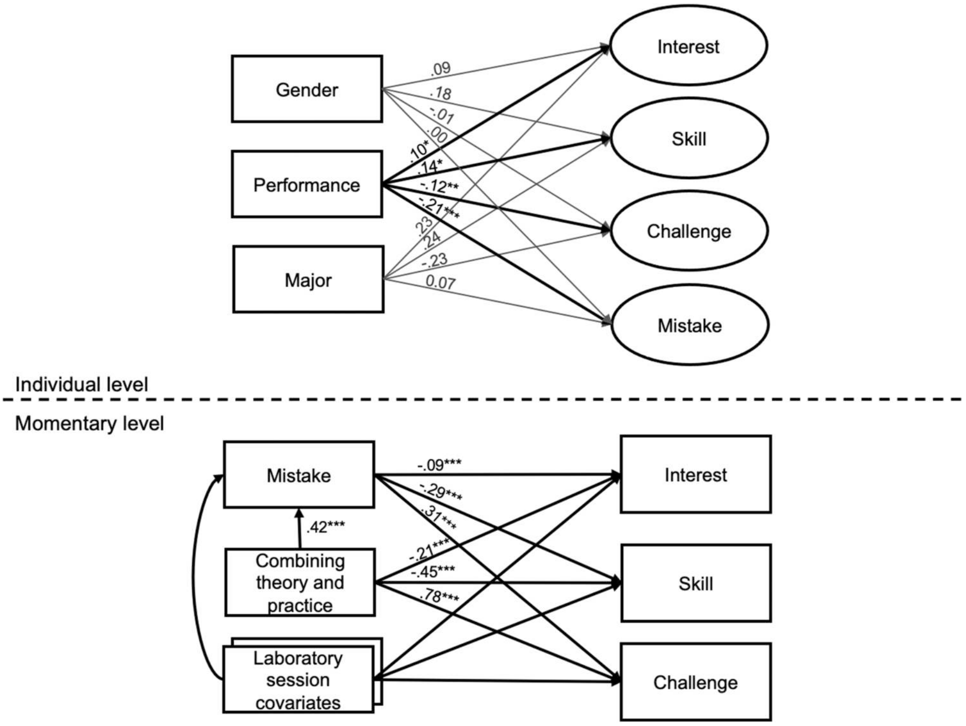

Figure 2. A two-level model that describes the effects of making mistakes on optimal learning elements, significant at * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$ levels. The values for laboratory session covariates are presented in Table 5.

Table 4. The results of the multilevel structural equation model on the effects of background variables on optimal learning elements on the individual (between) level.

	Interest			Skill			Challenge		
	β	S.E.	*p*	β	S.E.	*p*	β	S.E.	*p*
Gender	.09	.13	.51	.18	.13	.18	−.01	.12	.93
Performance	.10	.05	.02	.14	.05	.01	−.12	.04	.01
Major	.23	.13	.07	.24	.13	.07	−.23	.13	.07

Table 5. The results of the multilevel structural equation model on the effects of background variables on optimal learning elements at the situational (within) level.

	Interest			Skill			Challenge		
	β	S.E.	*p*	β	S.E.	*p*	β	S.E.	*P*
Making a mistake	−.09	.03	.001	−.29	.03	<.001	.31	.03	<.001
Combining theory and practice	−.21	.04	<.001	−.45	.06	<.001	.78	.05	<.001
Reference: Liquid-liquid extraction									
pH-titration	−.15	.06	.01	−.33	.09	<.001	.61	.09	<.001
Complexometric titration	−.15	.07	.03	−.21	.09	.01	.27	.09	.001
Buffer solutions	−.32	.05	<.001	−.39	.07	<.001	.56	.08	<.001
Reference: pH-titration									
Complexometric titration	.01	.05	.83	.12	.09	.18	−.33	.09	<.001
Buffer solutions	−.16	.06	.003	−.06	.07	.41	−.04	.07	.61
Reference: Complexometric titration									
Buffer solutions	−.17	.06	.003	−.17	.09	.05	.29	.09	.001

Table 6. The logistic regression model results in a 95% confidence interval for mistake claims on optimal learning moments.

			95% C.I.	
X on OLM	OR	S.E.	Lower 2.5%	Upper 2.5%
Mistake	0.73	.26	0.36	1.45
Mistake, practical	1.25	.48	.59	2.65
Mistake, computational	1.67	.71	.72	3.84
Mistake, teacher helped	0.85	.37	.36	1.99
Mistake, peers helped	1.09	.48	.46	2.58

Notes: Presented odds ratio (OR), standard error (S.E.) and the confidence interval.

Table 7. The results of the structural equation model on the effects of mistake claims on optimal learning elements.

	Interest			Skill			Challenge		
	β	S.E.	*p*	β	S.E.	*p*	β	S.E.	*P*
Mistake	−.21	.10	.05	−.53	.12	<.001	.39	.11	<.001
Mistake, practical	.24	.12	.04	.52	.13	<.001	−.43	.13	.001
Mistake, computational	−.22	.16	.17	−.41	.18	.02	.70	.15	<.001
Mistake, teacher helped	−.19	.13	.14	−.40	.16	.01	.35	.15	.02
Mistake, peers helped	.26	.16	.11	−.09	.15	.54	.44	.14	.001

Discussion

In almost one-third of all learning situations (29.0%) in this study, students noticed they had made a mistake, and there may have been even more mistakes that students did not recognise making. The frequent occurrence of mistakes emphasises the importance of understanding the effects of mistakes in more depth (cf. Huangfu et al., 2023; Käfer et al., 2019; Tulis & Ainley, 2011; Tulis & Fulmer, 2013). As might be anticipated, based on the two-level structural equation models, higher-performing students were less likely to commit mistakes in the laboratory. However, students' gender or major did not have a statistically significant effect on the frequency of mistakes.

Optimal learning situations, with higher-than-average levels of skill, interest, and challenge, constituted 11.9% of all situations included in the study. In line with previous studies (Schneider et al., 2016; Pöysä et al., 2020), individual characteristics, i.e. performance, gender, and major, did not have a statistically significant impact on the frequency of OLMs. However, students' performance did have an effect on the elements of optimal learning, as students with higher performance reported higher levels of interest and skill, and lower levels of challenge.

The MSEM-models also showed some statistically significant differences between the four laboratory sessions in the frequency of mistakes as well as in the levels of interest, skill and challenge. This highlights the importance of considering contextual factors when studying mistakes and situational engagement in a laboratory environment (cf. Schmidt et al., 2018; Atabek-Yigit & Senoz, 2023; Spicer, 2015).

Based on the momentary level results of the two-level structural equation models, students were more likely to experience OLMs during phases of laboratory work in which students were combining theory and practice. Previous studies have shown, that is rather common for students to conduct practical work absent-mindedly (e.g. Reid & Shah, 2007; Barrie et al., 2015; Galloway et al., 2016; Galloway & Bretz, 2015a), but our results implicate, that when the practical work instructions guide students into thinking of the underpinned scientific theories, cognitive learning could be activated, resulting in an increase in the level of their engagement. Although the students reported lower levels of skill and interest during these situations, combining theory and practice significantly increased the level of challenge reported by the students, promoting high situational engagement. During these moments, students were also more likely to make mistakes, which further reinforced the codirectional effect of theory-practice connections on interest, skill, and challenge.

Promoting this theory-practice-connections in the laboratory could be done by for example requiring calculations and posing students with questions about the theoretical background of the analysis method or results. It must be noted, however, that not all learning situations can be OLMs. It is important to ensure, that in addition to highly engaging learning situations, there are also enough pauses, breaks, or otherwise less demanding moments. Being highly engaged during the entire 3 – to 4-hour laboratory session might lead to a cognitive load too heavy to carry (Kirschner et al., 2011), and result in a decrease in achievement (Chang, 2018).

The frequency of OLMs was not affected by the type of mistake. However, if the error was computational, the negative effect of mistakes on skill and the positive effect on challenge were amplified. The effect was the opposite for practical mistakes. This is probably due to the cognitive demands of the computational phases of laboratory work being greater than the cognitive demands of the practical phases (cf. Galloway & Bretz, 2015b). If the laboratory experiments had consisted of more open inquiry tasks, which would have demanded more student creativity, for example in setting research questions or planning the experiment, the cognitive demands might have been higher also during non-computational phases (cf. Lamminpää & Vesterinen, 2018; Sadeh & Zion, 2009).

Based on the results that align with Inkinen et al. (2019) and Atabek-Yigit and Senoz (2023), we suggest, that the low challenge of laboratory work should be considered, as it seems to be the barrier to obtaining optimal learning moments. One way to do that, could be introducing more open inquiry or open-ended work instructions as an alternative to expository ones (e.g. Sadeh & Zion, 2009). This is supported by the results of Schmidt et al. (2018), establishing that having a choice in the laboratory contributes to higher situational engagement.

According to previous studies, the error climate in the laboratory and the student's trust in the teachers predict their openness to discuss their mistakes (Soncini et al., 2022; Leighton et al., 2018). Receiving support to solve the mistake impacted the reported levels of skill and challenge. As might have been expected, students were more likely to seek support from the teacher or their peers in solving the mistake, when the level of challenge was high. Seeking support from a teacher amplified the negative effect of mistakes on the experienced skill level. This does not mean, that seeking help from a teacher made students feel less skilled, as students might have just been more likely to seek support from teachers when they felt less skilled.

When students have a chance to communicate with each other during laboratory work, it is easier for them to seek help for solving mistakes with their peers. Generally, promoting dialogue in the laboratory seems to enhance meaningful learning (Seery et al., 2024). During this laboratory course students performed the experiments with a pair, enabling constant peer interaction. Based on the results of this study, being able to solve mistakes with peers seemed to maintain students' experience of their capability.

Teachers providing immediate support by solving problems without allowing students to solve them themselves can also pose a risk to student engagement. According to student interviews of Atabek-Yigit and Senoz (2023), immediate support given by the teachers when students asked for help led to students finding the experiments too easy. Therefore, providing students more opportunities to solve mistakes with peers, could maintain appropriate levels of challenge, promote a more positive error climate in the laboratory, enhance students' positive attitudes toward making mistakes, and help students in their self-regulation and adaptive reactions when mistakes occur (Tulis et al., 2016).

The importance of students' attitudes and the error climate of the learning environment (see Tulis & Ainley, 2011; Huangfu et al., 2023; Leighton et al., 2018; Käfer et al., 2019; Soncini et al., 2022; Galloway et al., 2016) highlights the need for further research on students' situation-specific emotions after making mistakes in a laboratory environment. Our results point out that making mistakes affects elements of engagement, which based on previous studies, are further associated with students' emotions (see Schneider et al., 2016). Learning enhancers, such as confidence, happiness, and enjoyment, as well as learning accelerators, such as stress and even anxiety have been found to positively correlate with OLMs (Schneider et al., 2016), and this should be researched from the perspective of making mistakes.

Study limitations

The results of this study show, that use of ecological momentary assessment (EMA) data in a laboratory environment is a valid approach to study multiple characteristics of laboratory learning simultaneously. However, the approach has some limitations. First, mistakes are not ambiguously defined. Students were asked if they noticed having made a mistake, but not what they understood by the term *mistake* (cf. Käfer et al., 2019). Secondly, as the data collection happened during laboratory sessions during which students have plenty of things to take into account without the data collection, the compliance rate was distinctly lower during laboratory session than during preparative online tasks. Thus, only within-level variables were used in models analysing the moderating effect of the types of mistakes and the forms of support used in solving the errors.

Conclusions

In conclusion, the purpose of this study was to investigate the relationship between situational engagement and situational characteristics in the laboratory (i.e. mistake situations, theory-practice integrations, experiments) as well as situational engagement and student characteristics (i.e. performance, gender, major) using MSEM. Our results suggest that strengthening theory-practice integrations could promote high situational engagement. Based on our results, making mistakes affects all elements of situational engagement (i.e. interest, skill, and challenge). Computational mistakes intensify, and practical mistakes reduce the decrease of interest and skill and the increase of challenge that occurs in all mistake situations. Seeking support after mistakes was associated with a higher challenge, while teacher support, in contrast to peer support, was also associated with a lower skill. Therefore, situational engagement could also be enhanced by encouraging students to solve mistakes in collaboration. Finally, the observed frequent occurrence of mistakes underscores the importance of conducting further research in this area.

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Disclosure statement

No potential conflict of interest was reported by the author(s).

Ethics statement

This research met the ethics requirements for research involving human subjects and followed the ethical guidelines of Finnish National Board on Research Integrity TENK. The research did not pose any risk to the participants, and it was not associated with high physical or emotional stress. All participants were informed about the absolute voluntariness of participation, the study objective, the protection of data privacy, the no-risk character of the study, and contact information for questions or problems.

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