

Article

Enhancing Molecular Biology Content Knowledge and Teaching Self-Efficacy in Pre-Service Teachers Through Virtual and Hands-On Labs and Reflective Teaching

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Abstract: Teachers in lower secondary education often lack content knowledge and self-efficacy to teach molecular biology. The focus of this study was to develop and evaluate an innovative educational approach to prepare pre-service teachers for teaching molecular biology. Therefore, an educational double-decker, with two master courses in a teaching-learning laboratory, has been developed. First, teacher students acquire virtual and authentic lab experiences in a blended-learning course. Later they gain reflective teaching experience by instructing peers or secondary school students. Using a mixed-methods approach in a one-shot-case study design, we examined the effects of the two courses on content knowledge of molecular biology and self-efficacy to teach it, the relationship between knowledge and self-efficacy, and the influence of teaching secondary students compared to peer teaching on self-efficacy. Questionnaires ($N = 92$ and $N = 20$) measured knowledge and self-efficacy before and after both courses; differences were analyzed statistically. In addition, guided interviews were conducted with teacher students after the educational double-decker ($N = 14$) and analyzed qualitatively using content analysis. The results demonstrate that blended-learning formats are efficacious in developing molecular biology knowledge. Content knowledge is positively correlated with teaching self-efficacy, but this effect diminishes after having a reflective teaching experience. These experiences are pivotal factors in self-efficacy development. Teaching real secondary school students is valuable in fostering self-efficacy, as such authentic experiences can be readily applied in everyday school life.

Keywords: molecular biology; teaching-learning-lab; reflection; virtual lab; teacher education



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1. Introduction

This study was conducted in a region where students complete primary school after grade 4. They then progress into distinct secondary school systems. One educational path prepares students for a national secondary school qualification (General Certificate of Secondary Education (GCSE)) in grade 10 (lower secondary education). This qualification allows graduates to directly enter the workforce or pursue vocational training programs. The other stream additionally prepares students for university entrance exams (A-levels) through grades 11 and 12 (upper secondary education). Starting from grade five, students

are no longer taught general science subjects. Instead, they receive specialized instruction in biology through dedicated biology courses, led by specially trained biology teachers.

The curriculum for lower secondary education includes a genetics unit. This unit focuses on concepts in cell biology and heredity, particularly the structure of genetic information. It also aims to assess the use of genetic engineering (e.g., in agriculture or drug manufacturing). However, a thorough evaluation of these topics is challenging without understanding the underlying molecular biology techniques. Notably, these techniques, along with the fundamental principles of molecular biology, are only introduced in the upper secondary school curriculum. Teachers in lower secondary education in this region show significantly lower content knowledge and self-efficacy compared to their colleagues working at schools that also offer upper secondary education (Haberbosch et al., *in press*).

Molecular biology has revolutionized all areas of biology over the last few decades and is having an increasing impact on everyday life. This was particularly evident in the past pandemic, where PCR-testing and mRNA-based vaccines were used to fight the spread of COVID-19. It was also observed that a big portion of the population faces challenges in accurately assessing the risks associated with mRNA-based vaccines (Fieselmann et al., 2022). This is hardly surprising, considering that a significant portion of the population leaves school after lower secondary education without having been exposed to molecular biology techniques. To prepare all future citizens to make informed decisions in these situations, everyone requires a solid understanding of molecular biology. To achieve this goal, we need biology teachers who can teach these molecular biology fundamentals even at the lower secondary education level to students, that will leave the educational school system after grade 10 in lower secondary education. Since molecular biology fundamentals have typically been taught only to high-achieving students in the later stages of their schooling, and educational research also tends to focus on this group (Duncan et al., 2011), this article demonstrates how pre-service teachers for lower secondary education can be prepared for this task.

1.1. Unlocking the Secrets of Molecular Biology Through Virtual and Authentic Lab Experiences

Teacher education programs play a crucial role in helping prospective educators to develop essential expertise in molecular biology and to prepare them to effectively teach the subject. The knowledge a teacher needs to understand the subject matter, including concepts, theories, and ideas, can be referred to as content knowledge (CK), following Shulman (1986). This content knowledge corresponds to declarative knowledge as defined by cognitive psychologist Anderson (2001), who developed the ACT (Adaptive Control of Thought) theory. Declarative knowledge, also known as “knowing what”, encompasses facts, concepts, and theories. Procedural knowledge, on the other hand, is described as “knowing how” and pertains to the knowledge of performing actions, typically of a practical nature.

Building the declarative knowledge of pre-service teachers in molecular biology is challenging due to the complex and abstract nature of the subject. The use of virtual laboratories, such as Labster, is a promising option that has shown success in the training of microbiologists and pharmaceutical toxicologists (Dyrberg et al., 2017) and biomedical students (Li et al., 2023). The RAT model (Hughes et al., 2006) serves as an assessment framework that enables educators to evaluate the impact of digital technologies in the classroom. It distinguishes whether a digital medium simply replaces an analog one (Replacement), enhances the efficiency of teaching (Amplification), or opens up new learning opportunities (Transformation). The use of virtual laboratories can represent a transformation of teaching by providing new opportunities for knowledge acquisition. For instance, virtual labs allow the application of state-of-the-art molecular biology techniques that

are often impractical in traditional educational settings due to safety regulations or financial constraints. Additionally, working in virtual laboratories can eliminate the lengthy time required for processes like PCRs or electrophoresis. These virtual laboratories often incorporate dynamic animations to visually represent in vitro processes, enhancing the comprehension of the subject matter (Strømme & Mork, 2021). In the past decade, empirical educational research has examined the effectiveness of virtual laboratories. Positive effects on learning outcomes using virtual simulations have been demonstrated in the field of molecular biology and genetics (Thisgaard & Makransky, 2017; Bonde et al., 2014; Sadler et al., 2015). Yu et al. (2022) found that when biology master's students encounter unexpected outcomes from simulation-based experiments, rather than those generated through their own experiments, they are more likely to reflect on the biological factors that could explain why their hypothesis was incorrect, instead of questioning their experimental abilities. Social interactions with other learners offer new learning opportunities. However, Schäfers et al. (2020) demonstrated that the use of digital labs diminishes social interactions among learners. However, they can have a positive effect on interest and encourage learners to pursue a career in the STEM field (Thisgaard & Makransky, 2017). Navarro et al. (2024) investigated the perceptions of Labster simulations (the same provider used for the virtual labs in this study) from the perspectives of first-year undergraduate students and their teachers in a cell biology course. Their findings highlighted that the primary strength of virtual labs lies in their ability to prepare students for traditional lab work, while also fostering positive learning attitudes. However, they also pointed out that using these simulations at home presents technical challenges, such as the requirement for a stable internet connection and a capable device. These concerns must be addressed, particularly in the context of educational equity.

In the region where the study was conducted, teachers also have the educational mandate through the curriculum to prepare students for potential careers in biology through practical work (Ministerium für Kultus, Jugend und Sport, 2022). Hands-on experiences in the laboratory enable a better understanding and application of abstract concepts, while also promoting critical thinking, problem-solving skills and teamwork (Hofstein & Lunetta, 2004). Although the question regarding the impact of hands-on laboratory work on learning outcomes has not been conclusively answered (Scharfenberg, 2005), conducting molecular biology experiments in the classroom could help make the abstract concepts visible and thus open the learners' eyes to the field of modern biology.

1.2. Enhancing Self-Efficacy in Teaching Molecular Biology Through Reflection

For some teachers, it is a challenge to teach abstract molecular biology in a practical, hands-on manner in the classroom (Gelamdin et al., 2013). Even if teachers are familiar with methods such as gel electrophoresis and polymerase chain reaction (PCR), they often lack the confidence to teach them, resulting in the avoidance of modern biology in the classroom (Boulay et al., 2010). This could be attributed to a lack of positive self-efficacy. Bandura (1977) defines self-efficacy as the belief in one's own abilities to organize and execute the actions required to accomplish a specific goal or task. According to Bandura (1997), enactive mastery experiences and vicarious experiences are the most influential sources for developing self-efficacy.

Teachers' self-efficacy, which refers to their personal confidence in effectively meeting subject-specific demands, plays a crucial role in their acceptance of challenging content (Franken et al., 2020) and is therefore particularly relevant in the context of teaching molecular biology. The number of science content courses a teacher takes during their studies is positively correlated with teaching outcome expectancy (Swackhamer et al., 2009), a subdimension of science teaching efficacy according to Riggs and Enochs (1990).

However, according to Taştan Kırık (2013) only a small portion of the variance in self-efficacy to teach science can be explained by the knowledge in this field. The initial teacher education phase is a crucial period for developing positive self-efficacy (Ilhan et al., 2015), and research-based positive teaching experiences serve as an effective means of achieving this objective (Makrinus, 2013). In a mixed-methods study conducted without a control group, it was found that teaching school classes had positive effects on the self-efficacy of pre-service teachers for instructional strategies, classroom management and student engagement. The qualitative data analysis highlighted the significant role of hands-on experience as a valuable opportunity in this regard (Brown et al., 2015). Furthermore, teaching can contribute to a deeper understanding of the subject being taught (Koh et al., 2018). However, vicarious experiences, along with subsequent reflection on them, can also contribute to the development of positive self-efficacy (Kinskey & Callahan, 2022). Reflection refers to a criterion-guided and systematic thinking process that focuses on specific actions, thoughts, or events (Wyss, 2013). It involves considering one's own values, experiences, and beliefs, as well as broader perspectives, including theoretical, ethical-moral, and societal aspects. Reflecting on one's own teacher personality and on the teaching process is crucial for personal development and ensuring the quality of teaching (Korthagen & Vasalos, 2005).

1.3. The Educational Double-Decker in the Teaching-Learning-Lab

An innovative course framework was developed and piloted in a “Teaching in Secondary Schools” master’s program to address two key needs: enhancing pre-service teachers’ content knowledge of molecular biology and fostering their self-efficacy in teaching it. This program prepares future educators for comprehensive schools where students aim to obtain the General Certificate of Secondary Education (GCSE) in grade 10. The curriculum is designed as a sequential “educational double-decker” (Wahl, 2013) consisting of two 14-week courses totaling 7 ECTS (European Credit Transfer System Points) (1 ECTS = 25 h workload). Teachers, especially those in lower secondary education (Haberbosch et al., *in press*), often lack confidence in teaching molecular biology in a practice-oriented way that is appropriate for their target group (Boulay et al., 2010). The educational double-decker approach allows pre-service teachers (many of whom are engaging with practical molecular biology teaching for the first time) to experience both the strengths and limitations of hands-on instruction firsthand. Switching between roles simulates a process of reflecting on one's own thinking and feeling during learning, while engaging with the theoretical foundations of the learning environment helps to reduce reservations, often rooted in a lack of adequate training, such as the belief expressed by teachers in interviews that molecular biology is *far too complicated* for lower secondary education (Haberbosch et al., *in press*), and opens the door to new perspectives on teaching molecular biology (Wahl, 2002). Both courses are conducted in a specialized molecular biology teaching-learning laboratory (details in Figure 1).

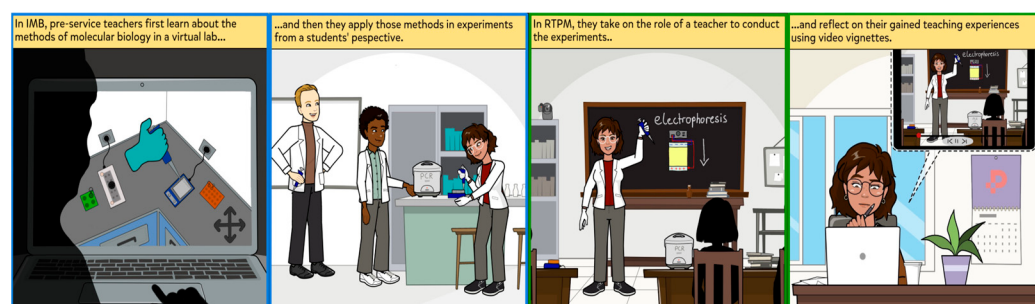


Figure 1. Overview of the educational double-decker for molecular biology in the teaching-learning lab.

The first course, Introduction to Molecular Biology (IMB) (3 ECTS), utilizes a blended-learning approach. Pre-service teachers independently delve into lecture materials and virtual labs at home, familiarizing themselves with core molecular biology concepts and methods. This sets the stage for interactive, hands-on activities in the on-site lab. The virtual labs come equipped with a virtual tablet, providing theoretical background and visualizations of in vitro processes. Learning is further reinforced through multiple-choice questions with immediate computer-based feedback (Đorić et al., 2021). Complementing the virtual world, the in-class laboratory sessions focus on the practical application of key methods like DNA extraction, gel electrophoresis, PCR, and sequencing. These techniques are not just learned in isolation; they are brought to life through engaging scenarios. Students solve a forensic murder case using genetic fingerprinting with gel electrophoresis. They combine Sanger and NGS sequencing with bioinformatics to identify arthropod species based on CO1 sequences. Additionally, students use PCR to amplify their PER3 gene and determine whether they are genotypic morning people or night owls based on the number of VNTRs (variable number tandem repeats) through subsequent gel electrophoresis. In the IMB course, the pre-service teachers observed a model lesson on how molecular biology can be taught in a practice-oriented way, with university students instead of actual school pupils. According to Bandura (1997), observing others successfully master challenges can enhance one's own self-efficacy beliefs. However, it remains unclear to what extent the pre-service teachers equate the instructors' teaching of university students with their own future teaching in schools, and how this observation actually influences their self-efficacy. The effectiveness of this combined approach—virtual labs and real-world applications—is mirrored in studies by Li et al. (2023), where senior undergraduate biomedical students successfully developed both theoretical knowledge and practical laboratory skills. The combination of virtual and physical labs is also suitable for teaching lab safety and molecular biology to lower secondary education students (Haberbosch et al., 2025).

After completing IMB, pre-service teachers enroll in the Reflecting on Teaching Practice Molecular Biology (RTPM) course (4 ECTS). Despite the importance of practical laboratory work for conducting experiments in scientific inquiry, less than 10% of upper-level biology classes are devoted to laboratory work (Dierkes, 2010). RTPM aims to develop their ability to reflect on their own biology teaching in a criterion-led manner and enables pre-service teachers to gain positive experiences in teaching practical laboratory work in the field of molecular biology within a reduced-complexity framework (e.g., smaller group sizes, support in lesson planning, and provision of materials). As a part of a teaching team, they plan a 90-min lesson on the practical teaching of molecular biology methods, using a school experiment on genetic fingerprinting in forensics that they learned during IMB. Their teaching sessions are recorded on video and then analyzed multiple times using video vignettes and professional guidance. Throughout the seminar, an improvement in reflective performance can be observed (Schaal et al., 2022). Dong and Gedvilienė (2025) examined the relationship between reflection and self-efficacy in a completely different context—the process of learning to play the piano. They demonstrated that reflection helps alleviate anxiety and enhance self-efficacy.

1.4. Preparation for the Reality Shock Through Teaching Real Students?

Upon entering the profession, many teachers experience the so-called reality shock. During this period, the ideals developed during their studies often collapse, and most young teachers go through identity crises (Dicke et al., 2016). This phenomenon is directly associated with a reduction in teaching self-efficacy (Klempin et al., 2020). Direct teaching experiences are the most influential factor in the development of teaching self-efficacy (Bandura, 1997). However, research on the impact of practical experiences, particularly

those involving pre-service teachers teaching real students, on teaching self-efficacy is inconsistent. While some studies show partially positive correlations (Franken et al., 2020), others frequently identify a negative relationship between teaching self-efficacy and the experiences of pre-service teachers in teaching real students (Rabe et al., 2012; Tschannen-Moran et al., 1998). Tschannen-Moran et al. (1998) therefore propose reducing the complexity of initial teaching experiences for pre-service teachers to avoid the reality shock. This could be achieved by having pre-service teachers teach peers instead of students, or if they are teaching real students, by reducing the class size, for example. Practical experience in initial teacher training also plays a crucial role in enhancing satisfaction with career choice (Villalobos Iturriaga et al., 2025).

2. Research Question

Teaching molecular biology is challenging, particularly in lower secondary education. Therefore, teachers' self-efficacy for the practice-oriented teaching of molecular biology is low (Boulay et al., 2010). To strengthen the teaching of molecular biology in lower secondary schools, an educational double-decker has been developed in the master's program for pre-service teachers. In this study, we investigate:

- (i) How does content knowledge of molecular biology and self-efficacy to teach it develop during IMB and RTPM courses?
- (ii) How does reflective teaching experience in the RTPM course influence the relationship between content knowledge and self-efficacy?
- (iii) What is the impact on pre-service teachers' self-efficacy when they teach secondary school students instead of fellow students (peer instruction)?

We hypothesized that the IMB course would influence both content knowledge and self-efficacy of pre-service biology teachers, as both virtual and practical lab work are suitable for building content knowledge in the taught areas (Hofstein & Lunetta, 2004; Thisgaard & Makransky, 2017), and content knowledge, in turn, has a positive effect on self-efficacy (Swackhamer et al., 2009). As teaching has a positive impact on self-efficacy (Makrinus, 2013) and can also lead to a deeper conceptual understanding (Koh et al., 2018), we also hypothesized that knowledge and self-efficacy of the pre-service teachers would develop in the RTPM course (i). Although the mechanisms underlying the gain in knowledge through teaching are not yet definitively clarified, one hypothesis suggests that, through interaction with inquisitive learners, teachers identify their own preconceptions and reconstruct their knowledge (Roscoe & Chi, 2008). On the other hand, it is debated whether the learning effect might simply be due to the repeated retrieval of information from memory (Koh et al., 2018). We hypothesized that there would be a low correlation between content knowledge of molecular biology and self-efficacy to teach it, as only a small proportion of teaching self-efficacy in science can be explained by science content knowledge (Taştan Kırık, 2013) (ii). We also hypothesized that the opportunity to teach school classes would have a positive impact on the pre-service teachers' self-efficacy in teaching molecular biology, as hands-on experience with students can be a crucial factor in the development of self-efficacy (Brown et al., 2015) (iii).

3. Methods

The Educational Design Research approach (McKenney & Reeves, 2018) served as the framework for the course and study design, with the goal of achieving full alignment between theory and practice. The project had two equally important goals:

1. To design a suitable course structure that enhances the quality of education in molecular biology in the master's program, and

2. To explore the development of and relationship between content knowledge of molecular biology and teaching self-efficacy during the courses IMB and RTPM.

In October 2017, the development of the blended-learning course (IMB) was initiated, followed by the establishment of RTPM in October 2020. These courses have been continuously optimized using the Educational Design Research approach in an evidence-based manner since their inception (McKenney & Reeves, 2018). In order to continuously develop the courses while maintaining the seminar concept, students were asked to make suggestions for improvement each semester through an anonymous questionnaire with open-ended questions. Responding to the desire for more practical experience in IMB, an additional practical experiment was integrated into both the summer semester of 2022 and the winter semester of 2023. English-language simulations were introduced starting in the summer semester of 2022 in the students' native language to reduce the language barrier. The study was initiated during the Covid-19 pandemic. Accordingly, the initial three-semester cohorts of the RTPM course could only teach pre-service teacher students in younger semesters through peer teaching (Group A). In the summer semester of 2022, secondary school classes were able to participate in the teaching-learning lab for the first time. This provided an opportunity to test the impact of different teaching scenarios on pre-service teachers' self-efficacy and to improve the course structure based on the Educational Design Research approach with the two last semester cohorts (Group B).

A mixed-methods approach was adopted to answer the research questions. The development of (i) and the relationship between (ii) content knowledge and teaching self-efficacy was predominantly measured quantitatively. Data were collected via an online questionnaire in a pre-post design for each course. The survey used a multiple-choice scale designed to assess content knowledge of molecular biology. In the AAAS Project 2061 (n.d.), items were created using common misconceptions identified in the literature and refined for content accuracy through collaboration with experts from the relevant fields, and then tested with several thousand students, with the datasets being publicly available. We selected 10 items from the AAAS portfolio based on their item difficulty and their alignment with the content knowledge that pre-service teachers will later need to teach based on the educational curriculum of the region, where the study was conducted. To obtain the overall score of content knowledge in molecular biology, we added up the number of correctly answered questions (a correctly answered question was scored as 1, an incorrectly answered question as 0). Despite the limited time available for questionnaire completion during the seminars, efforts were made to ensure comprehensive coverage of the content knowledge of molecular biology. Consequently, the reliability across all measurement points remained modest ($0.47 < \alpha < 0.7$), a challenge commonly referred to as the bandwidth-fidelity dilemma (Cronbach & Gleser, 1965). Self-efficacy for teaching molecular biology was assessed using a modified three-item scale ($\alpha = 0.80$) (Kauertz et al., 2011). As this is a field study under ecological conditions and as all pre-service teachers should receive the best possible learning opportunities, it would not be ethically justifiable to exclude a portion of the master students from the potentially promising educational intervention, which is why this study opted not to have a control group (Ramrathan et al., 2017). To support the validity of the quantitative data with a small sample size and gain further insights, guided interviews were conducted after the 2022 summer semester (iii).

3.1. Sample Description

All participants are enrolled in the secondary biology teaching master's program. The IMB course is a mandatory module for all students and has been offered eight times since October 2017, with an average enrollment of 20 students. All students were asked to complete the questionnaire on a voluntary basis before and after the seminar. The

questionnaire was completed by a total of $N = 92$ participants, with 83% being female. The average age of IMB students was 24.1 ± 3.2 years. The RTPM course has been offered five times since October 2020, with an average of six students enrolling in the elective course in the following semester after attending IMB. The sample size for RTPM is $N = 20$, with Group A consisting of $n = 8$ students and Group B consisting of $n = 12$ students. The average age of RTPM students is 22.3 ± 1.2 years. All RTPM students were invited to guided interviews via email acquisition. $N = 14$ (Group A: $n = 7$; Group B: $n = 7$) of the 20 potential interview partners accepted the invitation. $N = 14$ (Group A: $n = 7$; Group B: $n = 7$) of the 20 potential interview partners accepted the invitation. We conducted interviews with all students who were willing to participate.

3.2. Data Collection and Analysis

Quantitative data were collected from both seminars using an identical voluntary questionnaire, which did not affect students' examination performance. The online questionnaire was completed after the first and last session, taking an average of 24 min. To avoid duplicate evaluations, anonymous research codes were used to identify each participant's pre- and post-test responses. In an exploratory data analysis, using the Shapiro-Wilk test, a violation of the normal distribution of the data of content knowledge and self-efficacy were found in the pretest and post-test of the seminar IMB ($N = 92$, $p \leq 0.015$). The data of self-efficacy of the post-test in the seminar RTPM were also not normally distributed ($N = 20$, $p = 0.032$). Due to the violation of data normality, we utilized Wilcoxon signed-rank tests to examine our hypothesis regarding the positive effects of the IMB and RTPM courses on content knowledge and self-efficacy (i). It was also investigated whether there is a relationship between content knowledge of molecular biology and self-efficacy to teach it, and to what extent this is influenced by the reflective teaching experience gained in the RTPM course. For the analysis, one-way correlations (Spearman's rank correlation) were computed (ii). In September 2022 and March 2023, guided interviews were conducted with the graduates of the RTPM course. An interview guide was designed based on Bandura's theory of self-efficacy for this purpose. The interview guideline consisted of 5 questions, which aimed to capture the teaching self-efficacy of the pre-service teachers and to trace how this is influenced by the fact that secondary school pupils or fellow students were taught (iii). For example, the pre-service teachers were asked to *what extent the experience gained from planning, conducting and reflecting on the lessons influenced their views on teaching molecular biology in secondary schools*. In addition, they were asked about *the challenges of teaching molecular biology* and *whether they feel confident teaching molecular biology methods*. Additional follow-up questions were asked as needed to encourage interviewees to expand on their initial responses. Interviews were conducted in the presence of an external previously trained interviewer to reduce the effects of social desirability. To protect the anonymity of the respondents, only the anonymous research code was recorded in an accompanying questionnaire. Transcription was performed according to the simplified transcription scheme of [Dresing and Pehl \(2018\)](#) via a service provider.

The transcripts were evaluated using qualitative, structured content analysis according to [Mayring \(2015\)](#). This offers the possibility of overcoming the no longer contemporary view of the strict separation of qualitative and quantitative methods and allows the category-forming text analysis as well as the descriptive evaluation of the data. Following [Kuckartz \(2016\)](#), the entire text material was read hermeneutically-interpretatively at the beginning and text passages relevant to answering the research questions were marked. Subsequently, the deductive main- and subcategories derived from the research questions, following the work of [Schwarzer and Jerusalem \(2002\)](#), were formed. In a first run of material, the interviews were segmented, and the passages were assigned to each category. In

a second material run, additional inductively formed subcategories were added to the previous categories. In a third material run, all material was coded. Cross-tabulations were used to examine our hypothesis regarding the impact of teaching real secondary students compared to fellow students on the teaching self-efficacy of pre-service teachers (iii). To avoid biases caused by the small sample size, we ensured the selection of pre-service teachers of diverse genders (5 male, 9 female), varying ages (22–32 years old), and different educational backgrounds (biotechnological/pedagogical experiences, various types of school qualifications) and triangulated the findings with quantitative datasets. For example, it was examined to what extent the positive or negative self-efficacy observed in the interviews is reflected in the results of the self-efficacy scale in the questionnaire.

4. Results

The findings will be presented in three sections utilizing both quantitative and qualitative data. Firstly, the presentation will focus on the development of content knowledge in molecular biology and self-efficacy in teaching it (i). Secondly, the relationship between content knowledge and teaching self-efficacy will be explored (ii). These research questions will be addressed by utilizing quantitative data obtained from the analysis of questionnaires. Thirdly, the influence of different learning-teaching situations, specifically peer instruction versus secondary school pupils, on the development of teaching self-efficacy will be examined (iii). In line with a triangulation approach, the qualitative data gathered from guided interviews will be utilized and linked to the results based on the questionnaire.

4.1. Development of Content Knowledge and Teaching Self-Efficacy in the Teaching-Learning-Lab

The development of content knowledge and self-efficacy throughout the two courses is illustrated in Figure 2. Differences between content knowledge of molecular biology were found between the pretest and post-test in the IMB course. These were highly significant and showed a medium effect size (Döring & Bortz, 2016) ($N = 92$, $z = 4.44$, $p = 0.002$, $r = 0.46$). In contrast, there was no significant difference in knowledge in the pre-post-test of the RTPM course ($N = 20$, $z = 0.78$, $p = 0.44$). The self-efficacy to teach molecular biology differed highly significantly between the pre- and post-test in the seminar IMB but showed only a medium effect size ($N = 92$, $z = 4.79$, $p < 0.001$, $r = 0.49$). In contrast, self-efficacy for teaching molecular biology showed highly significant differences with large effect sizes (Döring & Bortz, 2016) between pre- and post-test of the course RTPM ($N = 20$, $z = 3.09$, $p < 0.001$, $r = 0.69$). To check whether there is a difference between the groups' IMB post and RTPM pre an additional Mann–Whitney U test was performed. No significant differences were found between the two groups for either content knowledge ($U = 784.50$, $p = 0.30$) or self-efficacy ($U = 847.00$, $p = 0.57$).

4.2. Relationship Between Content Knowledge and Teaching Self-Efficacy

To determine a potential relationship between content knowledge of molecular biology and teacher self-efficacy, a one-way correlation was performed. Knowledge of molecular biology correlated positively with self-efficacy to teach it before the RTPM course ($N = 20$, Spearman's $\rho = 0.392$, $p = 0.044$). This corresponds to a medium effect size (Döring & Bortz, 2016). However, after the RTPM course, there was no significant association between these two variables ($N = 20$, Spearman's $\rho = -0.024$, $p = 0.46$). The results depicted graphically in Figure 3 indicate that reflective teaching experience helps to mitigate the impact of knowledge of molecular biology on self-efficacy to teach it.

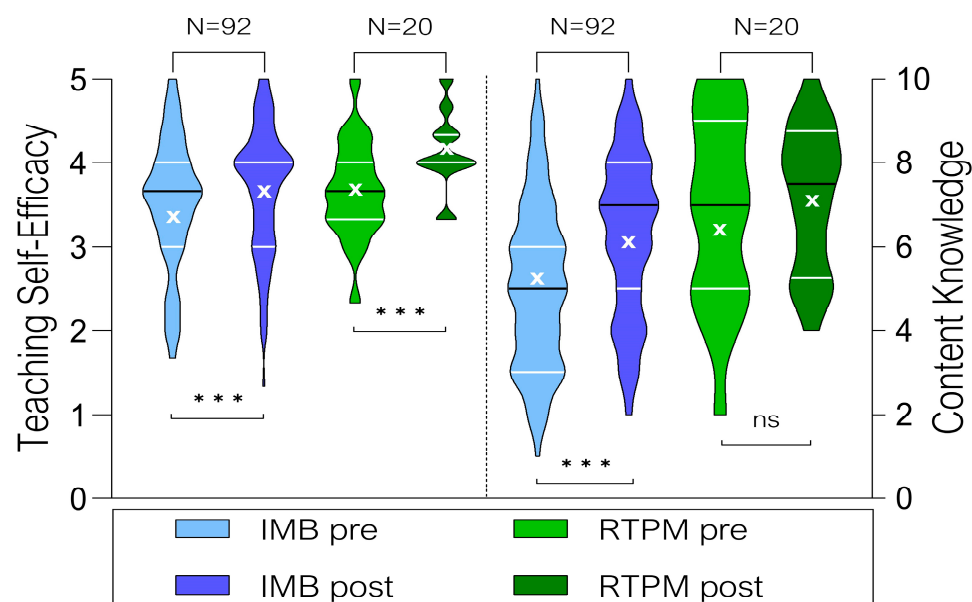


Figure 2. Progression of content knowledge and teaching self-efficacy in molecular biology across IMB and RTPM courses. Teaching Self-Efficacy was plotted on the left y-axis and measured using a 5-point Likert scale (5 indicates the highest self-efficacy), while the right y-axis displayed the total score of Content Knowledge (measured using a 10-item including single-choice test). The interquartile range was represented by white dots, with the solid black line indicating the median and the white cross representing the mean. The asterisks indicate the level of statistical significance: $p \leq 0.001$ (***) and ns stands for not significant.

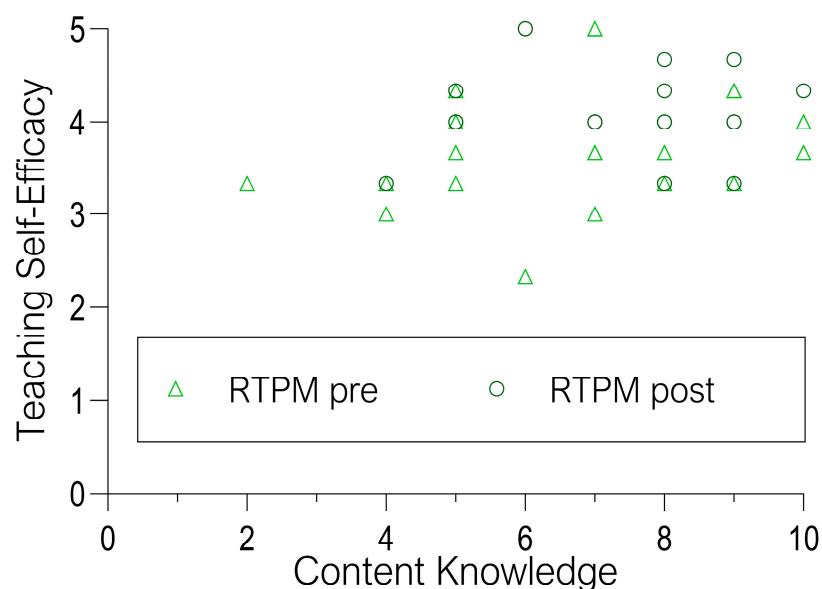


Figure 3. Relationship between content knowledge measured using a 10-item including single-choice test) of molecular biology and self-efficacy to teach it (measured using a 5-point Likert scale) before and after the course RTPM.

4.3. Impact of Peer Instruction vs. Teaching Secondary School Students on the Development of Self-Efficacy

The quantitative data's informative value is constrained by the limited sample size. To validate the findings, we conducted supplementary guided interviews. We inductively developed three subcategories for analyzing the pre-service teachers' self-efficacy development in the interview transcripts. The first subcategory encompassed self-efficacy before and after the seminar, which may not have been sufficient to teach molecular biology. The

second subcategory addressed self-efficacy regarding teaching molecular biology, which was already positive before the seminar. The third category emerged when students independently pointed out that their self-efficacy in teaching molecular biology developed through the seminar and their reflection on teaching experiences. Additionally, we explored the challenges pre-service teachers still perceived in teaching molecular biology after completing the “educational double-decker” and developed six subcategories from this exploration inductively.

In the interviews, $N = 3$ pre-service teachers still showed no positive teaching self-efficacy for molecular biology after completing the educational double-decker:

“It seems pretty complex. I don’t know if my students just can’t follow it there. That’s why I probably wouldn’t teach it, no”. (Segi22, Group A)

It is striking that all these pre-service teachers (highlighted in bold in Table 1) taught younger university students (peer teaching) in the RTPM course, not real secondary students. These students also demonstrated the lowest self-efficacy in the analysis of quantitative data. Furthermore, they stated that they could only transfer the findings gained from the peer instruction to everyday school life to a limited extent, since the prior knowledge and cognitive abilities of the teacher students are not comparable to secondary school students:

Table 1. Perceptions of Challenges and Self-Efficacy in Teaching Molecular Biology among Pre-Service Teachers: Insights from Guided Interviews with Peer Instruction and Secondary School Student Groups.

Participant	Group	Transferability to Everyday Teaching	Named Challenges	SubCategory Self-Efficacy in Interview	Self-Efficacy Questionnaire	Increase Self-Efficacy (Post-Pre)
Elst21	A	Limited *	1, 6a	-	3.33	0
Jabr25	A	yes	5	x (c)	N/A	N/A
Raso19	A	Limited *	1	x (b)	N/A	N/A
Roka02	A	yes	3, 4	x (b)	4.33	0
Segi22	A	Limited *	2, 5	-	4.00	0
Stsa27	A	yes	2, 5	x (b)	4.66	0.33
Vibo27	A	Limited *	1	-	3.33	0
Amka28	B	yes	1	x (b)	4.00	0
Anru24	B	yes	5	x (c)	4.00	0.33
Faan17	B	yes (with reference to 3)	6a, 6b	x (c)	4.33	0.67
Lima19	B	yes (with reference to 3)	1, 6b	x (c)	5.00	0
Mape20	B	yes	1, 3, 6a	x (c)	4.00	0.33
Heeh29	B	yes	6b	x (c)	4.00	0.33
Sobr03	B	yes	6b	x (c)	4.66	1.0

Note: x (b) = Positive teaching self-efficacy already present before the course; x (c) = positive teaching self-efficacy due to the course; - = no positive teaching self-efficacy observed. * = due to prior knowledge and cognitive abilities of fellow students taught. 1 = Nature of molecular biology (abstract and complex); 2 = Lack of time; 3 = Lack of equipment in schools; 4 = Lack of practical experience of the students; 5 = Lack of prior knowledge; 6 = Subject-specific educational challenges (6a= Dealing with Terminology; 6b = Identify core concepts). N/A: No data records are available for RTPM post.

“The workshop [...] can’t be transferred to everyday teaching because it was just fellow students. And with pupils, it would have been quite different, and we would have had to structure the workshop quite differently. Just from the terminology, the drawings and the methods we used [...], we would have had to do it completely differently”. (Elst21, Group A)

$N = 3$ pre-service teachers showed positive self-efficacy in the interviews but indicated that they already had this self-efficacy before the seminar, attributing it, for example, to their personal teaching experiences outside their university education:

“I actually never had any qualms about teaching it [molecular biology], neither before nor after, [...] but I also work part-time [at a commercial learning lab] and offer various courses on molecular and microbiology there”. (Roka02, Group A)

Only one pre-service teacher, whose statements were assigned to the subcategory showing positive self-efficacy before the seminar, showed a change between pre- and post-test (difference = 0.33). However, only one of the $N = 7$ pre-service teachers whose statements were assigned to the subcategory “positive teaching self-efficacy due to the course” showed no change between pre- and post-test in the quantitative data. All others showed differences from 0.33 to 1.0 and/or explained in the interviews that their self-efficacy changed due to the course:

“I was able to experience that the kids, if you convey the learning content correctly and if you build a cool story around it and if you use clear presentations, then you can very well teach molecular biology in an illustrative way. For me, this has taken away the fear of trying to teach it by myself later on”, (Mape20, Group B)

“So, just by the fact that I now, I would say, dare to approach molecular biology, which I would have immediately denied before, that I do that in class. (laughs.) But once you have familiarized yourself with it and reflected on everything, you realize that you can also teach it well”. (Jabr24, Group A)

It is noteworthy that all pre-service teachers who taught real students showed positive developments in self-efficacy in the interviews, and their differences in questionnaire scores between post and pre-measurements are also greater than those of students who conducted peer teaching. Students who conducted their lessons with school classes were also more likely to mention subject-specific educational challenges, such as dealing with terminology or identifying core concepts of molecular biology, than students who taught their peer group:

“Those are difficult words, long words, greek words, latin words, I always think that’s difficult. [...] you have to be smart to be able to translate that so that someone [...] can get excited and interested in the subject”. (Mape20, Group B)

“I think it is extremely difficult to identify the core concepts within the subject. I think it’s important to think about: Okay, what is actually the important thing about molecular biology? What is the exciting thing? What is the idea that I want to get across? And then implementing that, yes, I think that’s very challenging”. (Lima19, Group B)

Table 1 provides an overview of the findings from the guided interviews and compares them with the self-efficacy levels reported in the RTPM course questionnaire (means of the five-point Likert scale).

5. Discussion

5.1. Development of Content Knowledge and Teaching Self-Efficacy in the Teaching-Learning-Lab (i)

The results of this study showed that blended-learning formats (used in the course IMB) can be suitable for developing knowledge of molecular biology in teacher education. Future research is needed to determine the role the combination of virtual and hands-on laboratory experience plays in this regard. Although we hypothesized that teaching would lead to a deeper understanding of molecular biology content (Swackhamer et al., 2009), there was no significant change in content knowledge observed in the course which encouraged focused reflection on the conducted lessons in molecular biology (RTPM). The lack of change in content knowledge in this course could be attributed to the measurement

instrument's focus on declarative knowledge through 8 out of 10 items, while the practical execution of experiments with students may have primarily influenced procedural knowledge. Further subsequent studies should explore this hypothesis. However, the process of creating written reflections could also be meaningful for the blended-learning course, as crafting reflective journals has been shown to support the development of knowledge in molecular genetics within a third-year senior student's course (Tammu, 2022).

Both courses enhanced self-efficacy to teach molecular biology. This could be interpreted to mean that the model lessons conducted by the instructors in the IMB course were perceived by the pre-service teachers as vicarious experiences related to teaching molecular biology, which, according to Bandura (1997), can contribute to an increase in self-efficacy. However, it was confirmed that especially personal teaching experiences—as provided in the RTPM course—are more effective in enhancing pre-service teachers' self-efficacy in teaching molecular biology. However, it is uncertain which part of this effect can be explained by the mere teaching experience or the reflection of it. Dong and Gedvilienė (2025) included a control group in their study, which was also deliberately subjected to emotional manipulation and stress—an approach that would be ethically unthinkable for our study (see Limitations). However, their findings on the development of self-efficacy in piano playing demonstrated that it is, in fact, reflection that has a positive impact on the growth of self-efficacy. In upcoming studies, we aim to investigate whether this also holds true for teaching molecular biology by increasing our sample size and adjusting the timing of data collection. Rothe and Göbel (2024) also demonstrated that collegial reflection within peer groups of pre-service teachers can be effective. This could also be a potential avenue for the further development of our course in the context of EDR.

5.2. Relationship Between Knowledge and Self-Efficacy (ii)

While most studies examining the relationship between content knowledge and self-efficacy have focused on pre-service elementary teachers and have found only a small (Taştan Kırık, 2013) or no relationship (Menon & Sadler, 2016), we found a medium effect size correlation between knowledge of molecular biology and self-efficacy to teach it (Spearman's $\rho = 0.392$, $p = 0.044$). This could highlight the relevance of acquiring a deeper understanding of complex scientific concepts like molecular biology for pre-service secondary school teachers. However, after engaging in the reflective teaching experience, no correlation was found between the two variables. Nevertheless, comparisons with studies on elementary teacher education should be interpreted with caution, as the content knowledge and self-efficacy dimensions investigated in this study are very specific, with a strong focus on molecular biology, and our pre-service teachers are being prepared to teach in secondary schools. The relationship between knowledge and teacher self-efficacy, therefore, remains an area that requires further exploration and investigation.

5.3. Impact of Peer Instruction vs. Teaching Secondary School Students on the Development of Self-Efficacy (iii)

During the 2022 summer semester, lower secondary education classes were welcomed to the teaching-learning lab for the first time. To explore how pre-service teachers can be prepared for the decline in self-efficacy during the reality shock, we adopted a qualitative research approach. By comparing the self-efficacy development of those who taught peers with those who taught real students, we aimed to assess the impact of reflective teaching experiences. The interviews were conducted in September 2022 and March 2023. The teaching experience was about one year ago for Group A (Peer Teaching). Group B (student-teaching) had recently completed the seminar. It is conceivable that the different time spans between course attendance and the interview may skew the results of the qualitative data. To counteract this bias, we interviewed Group B no earlier than eight

weeks after the end of the seminar. We did not want to increase the amount of time between interview and course attendance for Group B, to prevent participants from dropping out of the study. We found that teaching real students may be beneficial because the (mostly positive) experiences gained in the course can be transferred to everyday teaching. We invest a considerable amount of time in preparing the students for teaching. While we did not collect data on the students' experiences in the teaching situations, our observations and written reflections of the pre-service teachers, which we analyzed in a different context, did not provide any indication of negative teaching experiences. Our study findings are consistent with [Franken et al. \(2020\)](#), who also reported an increase in self-efficacy through gaining experience in teaching students. In contrast to the typical literature depiction of a decrease in self-efficacy due to teaching experiences ([Rabe et al., 2012](#); [Tschannen-Moran et al., 1998](#)), we did not observe this trend. However, this could also be attributed to the fact that students in our seminar rarely encountered negative experiences.

One of the most significant challenges in teaching molecular biology, as perceived by practicing educators, is the time required for preparation ([Haberbosch et al., in press](#)). To enable educators (equipped with the necessary knowledge and self-efficacy), to effectively teach molecular biology in a practical manner within an everyday classroom setting, they require an infrastructure that facilitates the seamless acquisition of essential reagents. An exemplary model for this can be the one developed by [Sachyani et al. \(2023\)](#) for Israeli schools.

6. Limitations

Teaching molecular biology earlier than at the upper secondary level is not yet widespread. In the past, educational research also focused predominantly on older, higher-performing learners. Accordingly, meaningful approaches and concepts for teaching at the lower secondary level needed to be developed and tested for teacher education. To better interact with students, we only allowed a small group size. Therefore, the sample size (especially for the quantitative data on the RTPM course) is based on a low number of participants. However, utilizing small sample sizes can also have advantages as it facilitates systematic replication and extension of scientific findings ([McDermott, 2023](#)). This is particularly valuable in the context of the Educational Design Research approach employed in this study, as the developed and evaluated teaching concepts can be transferred and replicated in other disciplines. The results of statistical tests are sensitive to sample size; however, it is crucial to consider that the sample may not be representative, which is often challenging to achieve, especially in educational research where contexts vary widely across countries due to differences in educational systems. Therefore, the results are specific to the cohort studied and should not be generalized as universally applicable. Instead, they must be interpreted in the context of the educational system and the specific cohort under investigation. Nonetheless, the reliability of the quantitative data for this cohort were substantiated through triangulation with qualitative data.

This study has some limitations that should be considered in further research projects. No pre-service teacher should be excluded from the theoretically promising educational double-decker. Therefore, this study lacks a control group. It cannot be confirmed that the observable changes in content knowledge and teaching self-efficacy are due to the interventions. However, no other courses with a molecular biology focus are found in the master's program, which would explain an increase in expertise. In addition, some participants in the guided interviews cited the seminars as critical to developing their teaching self-efficacy even without prompting.

The field of molecular biology encompasses a broad spectrum of knowledge. The courses covered topics such as molecular biological methods, mechanisms of gene regula-

tion, inheritance processes, and the pathway from gene to protein. In the development of the study, specific items were chosen for a short scale to adequately represent the multidimensionality of the field of molecular biology knowledge. However, due to the diversity of the construct, this affects the reliability (Moss, 1994). Instead of limiting the scale to a few facets of molecular biology knowledge, there are plans to increase the sample size and statistical power in the future to capture the various dimensions of knowledge more comprehensively in the scale.

Furthermore, this study is limited by the fact, that the development of the course structure, the implementation of the lessons of the two courses and the analysis of the data were made by the authors themselves. However, the coding and analysis of the data were conducted blindly due to the anonymization of the students by the research code. To reduce the effects of social desirability, an independent interviewer was trained who assured participants that their statements would be anonymous.

7. Conclusions

The blended-learning course (IMB) was found to be effective in building up pre-service teachers' content knowledge in the domain of molecular biology. The combination of virtual labs and hands-on lab experience also had a positive effect on self-efficacy to teach molecular biology. The reflective teaching practice module (RTPM) was found to have significant and, notably, even greater effects on the development of self-efficacy, without necessarily promoting additional knowledge acquisition. Notably, the degree of knowledge in molecular biology was positively correlated with self-efficacy before RTPM. After RTPM, no significant relationship was found between content knowledge and self-efficacy, indicating that the reflective teaching experience outweighs the influence of knowledge of molecular biology on the self-efficacy to teach it. Teaching secondary school classes instead of fellow students is beneficial because single pre-service teachers partially doubt the transferability of their reflective teaching experiences with peer instruction to everyday school life. These students have not been able to build positive self-efficacy to teach molecular biology during the course. In addition, the reflected teaching experience with real students fosters the identification of subject-specific educational challenges. This study highlights effective approaches for preparing pre-service teachers to successfully teach challenging and abstract scientific content like molecular biology, by bridging the gap between theory and practice.

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Data Availability Statement: The data presented in this study are available upon request from the corresponding author. Due to the small sample size, it cannot be ruled out that the anonymized data (particularly the interviews) may allow for conclusions to be drawn about individual participants.

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