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The Effectiveness of Digital vs. Analogue Teaching Resources in a Flipped Classroom for Undergraduate Focus Cardiac Ultrasound Training: A Prospective, Randomised, Controlled Single-Centre Study

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Abstract

Introduction: This study investigated the effectiveness of e-learning compared to traditional teaching methods in ultrasound education, centring on a focus cardiac ultrasound (FoCUS) course for third-year undergraduate medical students. With the rise of digital teaching methods, it is essential to evaluate their impact on the development of theoretical and practical skills in ultrasound training. **Methods:** A prospective, randomised, controlled trial was conducted involving two groups of students participating in a one-day FoCUS course delivered in a flipped classroom format. The study group used e-learning resources, while the control group used hard-copy lecture notes. Assessments were conducted at three stages: before the course, during the preparation phase, and after the course. Evaluations included self-assessment surveys, theory tests, and practical exams using direct observation of procedural skills (DOPS) tests. The study group had 15% less practice time compared to the control group. **Results:** A total of 109 complete datasets (study group, n = 52; control group, n = 57) were analysed. Both groups showed an equivalent initial level of and a continuous and significant ($p < 0.01$) increase in subjective and objective skills over the evaluated time frame. The study group achieved significantly ($p = 0.03$) higher results in DOPS (T2) than the control group. No significant differences were found in the total scores of the theory tests (T2 + T3) or DOPS (T3). Both groups rated their teaching materials, motivation, and the course concept in similarly high scale ranges. **Conclusions:** The findings suggest that e-learning is as effective as traditional methods in developing ultrasound skills and may serve as a viable alternative, even with reduced face-to-face interaction. These results indicate that accreditation processes could be applied similarly to those for traditional formats without requiring in-person training as a prerequisite for quality

Keywords: ultrasound education; blended learning; flipped classroom; e-learning; ultrasound training; ultrasound curriculum; analogous teaching; digital teaching; FoCUS cardiac ultrasound

1. Introduction

Ultrasound is an important imaging procedure for visualising and assessing the heart diagnostically (Hagendorff et al., 2020; Werdan et al., 2020). Recent technological advances, particularly in mobile diagnostic devices, have increased the flexibility of cardiac examinations for a variety of health issues (3–8). In this context, terms such as 'clinical echocardiography', 'emergency echocardiography', and 'focused cardiac ultrasound' (FoCUS) have emerged to distinguish between various examination approaches and competenc requirements (Hagendorff et al., 2020, 2013; Neskovic et al., 2014, 2013, 2018; Spies et al., 2019; Tanner et al., 2020). FoCUS in particular is playing an increasingly prominent role in both initial assessment and follow-up care, especially in fields such as emergency and critical care medicine, where it is frequently performed by non-cardiology specialists (Breitkreutz et al., 2009; Johri et al., 2018; Neskovic et al., 2014, 2018; Yamada et al., 2022).

Various professional associations provide recommendations for theoretical and practical training in cardiac ultrasound (Breitkreutz et al., 2009; Neskovic et al., 2013, 2018; Popescu et al., 2009, 2020; Tanner et al., 2020; Werdan et al., 2020). Alongside completing certified courses, supervised independent practice of a defined number of exercises remains a cornerstone of these recommended medical training processes. Specialist societies and professional associations also favour the integration of ultrasound training into medical courses, which is increasingly occurring (Neubauer et al., 2024; J. Weimer et al., 2023a, 2023b). Preliminary studies have already shown that after (extra)curricular training, students on these courses can visualise the standard main echocardiographic sections and recognise simple pathologies (Gradl-Dietsch et al., 2018; Kobal et al., 2017; Kühl, 2012; J. Weimer et al., 2023b).

The digitalisation of medical ultrasound education was accelerated by the COVID-19 pandemic (Blank et al., 2022; N. J. Soni et al., 2021; Stoehr et al., 2021). In particular, the use of webinars, blended learning, and e-learning (also known as electronic learning) became the focus of curriculum adaptation (Blank et al., 2022; Harel-Sterling, 2023; Hari et al., 2020; Herbert et al., 2022; Röhrig et al., 2014; V. D. Soni, 2020; A. M. Weimer et al., 2023). In general terms, e-learning refers to the combination of digital technologies with educational processes and thus encompasses a wide range of digital teaching methods and resources (Darras et al., 2021; Harel-Sterling, 2023; Ruiz et al., 2006).

The advancement of digital technologies, particularly e-learning, has opened up new educational opportunities that are increasingly visible in FoCUS training (Cosyns et al., 2015; Fuchs et al., 2018; Guze, 2015; Harel-Sterling, 2023; Popescu et al., 2020; Torabi et al., 2021). Learners have access to a variety of multimedia resources such as online lectures/webinars (Herbert et al., 2022), online courses (D. Hempel et al., 2016; Torabi et al., 2021), apps (Obeng-Okyere et al., 2019), interactive simulations, and virtual anatomy models (Canty et al., 2019; Weber et al., 2019), that each allows them to learn at their own pace and explore the principles of ultrasound examination individually (Cosyns et al., 2015;

Ding et al., 2024; Harel-Sterling, 2023; C. Hempel et al., 2020; Lien et al., 2023; Ruiz et al., 2006). However, research suggests that the traditional methods or 'analogue' resources of ultrasound teaching should not be supplanted by digital resources, but rather the latter should be seen as complementary to the former (Blank et al., 2022; Harel-Sterling, 2023; Ruiz et al., 2006). This is because the use of traditional textbooks/lecture notes (Skrzypek et al., 2018; J. Weimer et al., 2023b), instructor-led demonstrations, and practical training on physical models (Shehata et al., 2022; J. Weimer et al., 2023b) provide tangible, tactile learning experiences and direct interaction with instructors. These methods are therefore essential for sound, holistic training in medicine (Dieden et al., 2019; Gradl-Dietsch et al., 2018; Popescu et al., 2020; J. Weimer et al., 2023b, 2024; Werdan et al., 2020).

Research Focus and Aim of the Present Study

In current ultrasound education, efforts have begun to combine traditional analogue teaching with digital teaching (a method referred to as 'blended learning'), often implemented in a so-called flipped classroom in which students arrive to a class having previously engaged with learning content independently, while the educator takes on the role of a facilitator who guides application and discussion rather than delivering traditional lectures (Blank et al., 2022; Harel-Sterling, 2023; Jujo et al., 2022; Neubauer et al., 2024; Tarique et al., 2018; A. M. Weimer et al., 2023). While several studies have explored the effectiveness of digital and analogue resources in ultrasound education, few have directly compared their impact within a flipped classroom approach (Harel-Sterling, 2023; Haskins et al., 2018; Neubauer et al., 2024; Tarique et al., 2018; J. M. Weimer et al., 2024). A recently published study showed that a group with e-learning preparation was able to achieve a similar level of preparedness for practical sessions with less preparation time compared to a group with analogue lecture notes (J. M. Weimer et al., 2024).

This second digital versus analogue study (DIvAN II) investigates whether preparation using e-learning can reduce the amount of hands-on time required for learning in a FoCUS flipped classroom model compared to preparation using analogue lecture notes. By employing both subjective and objective measurement methods, the study aims to evaluate attitudes towards ultrasound education through digital learning, motivation to engage with digital teaching materials, and the development of theoretical and practical skills with digital learning. This is intended to promote the evidence-based optimisation of resources for modern ultrasound training.

2. Materials and Methodology

2.1. Study Design, Participant Recruitment, and Study Procedure

This monocentric, prospective, randomised, controlled trial (Figure 1) was conducted during the summer semester of 2022 at a university hospital in Germany with a well-established ultrasound teaching infrastructure (Abplanalp et al., 2025; Duncan et al., 2020; Moher et al., 2010). Within the setting of an extracurricular workshop 'focused sonography of the heart' (J. Weimer et al., 2023b), a newly developed e-learning course was evaluated in comparison to a set of lecture notes with equivalent content. The e-learning workshop was a blended-learning-based flipped classroom (57). The study groups ('preparation via e-learning', $prep^{digital}$) and the control group ('preparation via lecture notes', $prep^{analogue}$) were defined. The practice times of the study group were intentionally reduced by 15% to determine whether learning efficiency could be improved with e-learning preparation in comparison to the lecture notes.

Participants were recruited via an official advertisement sent to a mailing list by the Student Affairs department of the university clinic. The course was voluntary and extracurricular in nature. Eligible participants were third-year undergraduate medical students to include as many inexperienced participants as possible. The participants had the opportunity to register for four possible course dates via an online portal. After completing the registration phase, participants were randomly assigned to one of four available course dates through the online registration portal. Two of these courses were predefined for the study group ('preparation via e-learning', prep^{digital}), and the other two for the control group ('preparation via lecture notes', prep^{analogue}). This resulted in a random group allocation without stratification or blocking, as students were unaware of the group assignment associated with each date.

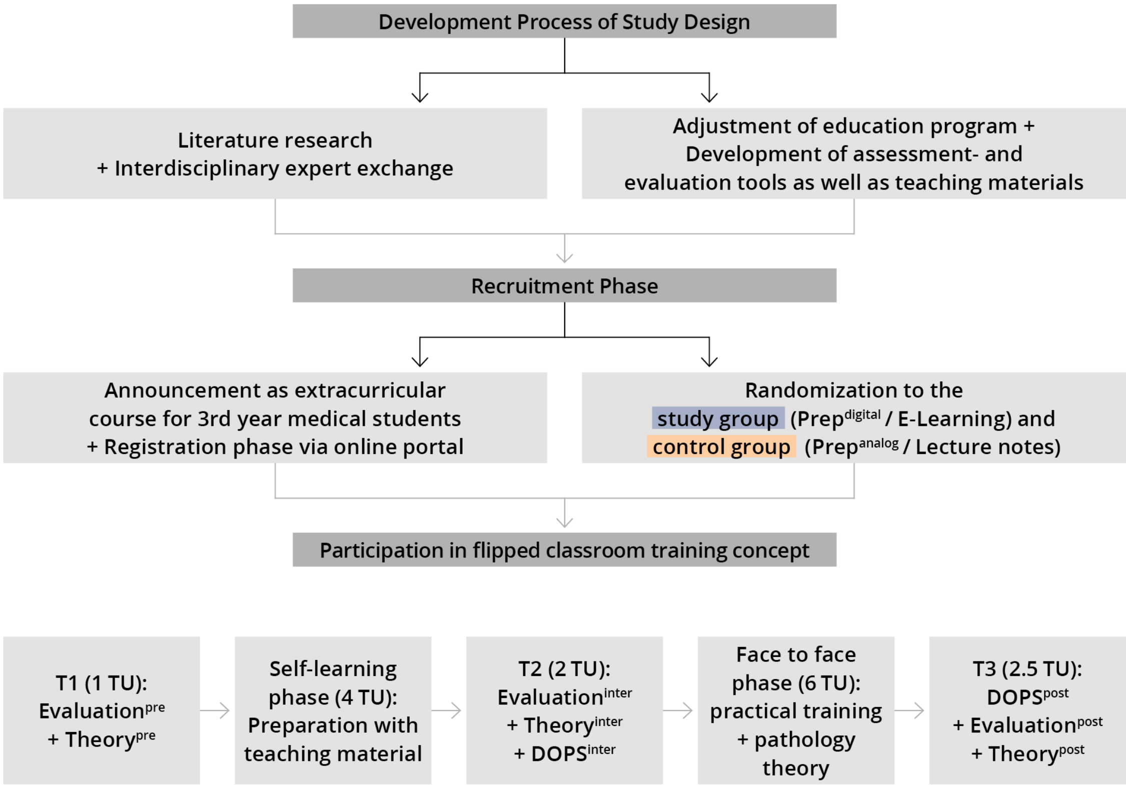

Figure 1. Chronological representation of the whole study development and procedure, including data collection times. The practice times of the study group were intentionally reduced by 15%. TU = teaching unit of 45 min each.

Evaluations (Evaluation^{pre}, Evaluation^{inter}, Evaluation^{post}), written tests (Theory^{pre}, Theory^{inter}, Theory^{post}) and practical direct observation of procedural skills (DOPS^{inter}, DOPS^{post}) tests were carried out at various points in time (T1 = pre, T2 = inter; T3 = post) (Höhne et al., 2022; Puthiaparampil & Rahman, 2020).

Pseudonymisation was carried out using a unique code defined by each participant at the time of initial data entry. This self-generated code enabled consistent linkage of questionnaire responses, test results, and practical exam data across all time points. No identifying personal information was stored with the research data, and the code remained known only to the participants.

Inclusion criteria were passing the 1st state exam and full participation in both the workshop (including the introductory meeting) and the examination formats. The primary endpoint focused on subjective and objective growth in theoretical and practical competence. Secondary endpoints assessed subjective satisfaction with the teaching concept and materials, as well as motivation.

2.2. Formulation of Training Concept

The training concept (see Figure 1), consisting of a total of 16 teaching units (TU = 45 min), was based on preliminary work (Greim et al., 2017; Price et al., 2008; J. Weimer et al., 2023b) and was slightly modified for the implementation of the study. It was based on the transthoracic echocardiography sectional views suggested by the World Interactive Network Focused on Critical Ultrasound (Via et al., 2014).

The course was divided for both groups into a pre-course phase (introduction + independent preparation using teaching materials), course phase (attendance phase with theory and practical training), and post-course phase (independent follow-up) (Stockwell et al., 2015; Tolks et al., 2016). The schedule and teaching objectives can be found in Supplements S1 and S2. The practice times of the study group were reduced by 15%. This design choice aimed to explore whether digital preparation could enhance learning efficiency by compensating for a shorter practical exposure, an increasingly relevant consideration in resource-constrained educational settings.

2.3. Procedure of the Training Concept

During the introduction (T1), all participants were presented with the course concept, including the learning objectives, and they completed an evaluation ($\text{Evaluation}^{\text{pre}}$) and a theoretical test ($\text{Theory}^{\text{pre}}$).

Participants had at least 1 week and a maximum of 2 weeks until the attendance phase. At the start of the in-person course phase (T2), all participants completed a further evaluation ($\text{Evaluation}^{\text{inter}}$), a theoretical test ($\text{Theory}^{\text{inter}}$), and a practical test in the form of a direct observation of procedural skills ($\text{DOPS}^{\text{inter}}$) (Höhne et al., 2022; J. M. Weimer et al., 2023a). Subsequently, peer tutors, working under the supervision of physicians, taught theoretical and practical lessons in small groups (4–5 students per group) (Dickerson et al., 2017; J. Weimer et al., 2025). All peer tutors underwent systematic training in advance to prepare them (Dickerson et al., 2017; J. Weimer et al., 2023b) and received a detailed briefing before each course date.

At the end of the face-to-face course phase (T3), all participants completed a final evaluation (evaluation post) with a theoretical test ($\text{theory}^{\text{post}}$) and three out of six potential DOPS examinations ($\text{DOPS}^{\text{post}}$). For the course follow-up, the participants were able to use the e-learning independently.

2.4. Teaching Materials

Both learning formats—lecture notes and the e-learning module—covered the same thematic structure, including learning objectives, anatomical basics, key clinical questions, sonographic instructions, standard cross-sections and measurements, and checklists for theory and practical tasks. The analogue version consisted of printed text, presented as continuous text and bullet points, with color-coded design elements to highlight summaries and checklists. It included labelled static images in varying formats, but no video content. In contrast, the e-learning module was web-based and required an internet connection. It offered the same content in a digitally structured format with interactive navigation, zoomable and clickable images, and embedded videos illustrating normal scanning procedures. While the lecture notes supported passive reading, the digital format promoted active engagement through quizzes with immediate feedback and interactive learning elements. Further information on the teaching media can be found below.

2.4.1. E-Learning

Based on the learning objectives of the course (J. Weimer et al., 2023b) and recommendations from prior studies (Heinz, 2016; Price et al., 2008; Via et al., 2014), an e-learning programme was developed with the involvement of sonography experts, didacticians, and IT specialists. The structure of the e-learning with examples can be found in Supplements S3–S5. The e-learning was accessed via a web browser. It consisted of a 'basics' section (that taught ultrasound physics, image production, and topographic anatomy) and a 'heart-specific' section with several equivalent standard chapters (that taught tips for probe handling, plane orientation and optimisation, sonoanatomy, and examination questions and protocols). The e-learning was built around individual learning cards ('slides'). Users called up continuous text, key points, images, and video clips via click functions to follow the learning content and the examination procedures. Further interactive click functions facilitated the answering of questions or labelling of empty tables or graphics.

2.4.2. Hard-Copy Lecture Notes

An existing course manual (J. Weimer et al., 2023b) was edited and served as the basis for the development of the e-learning. The lecture notes contained the same slides of the e-learning in printed form plus additional memo boxes.

2.5. Test and Evaluation Instruments

The test and evaluation tools were developed through an expert consensus process involving multiple iterative rounds of discussion among ultrasound specialists and medical education experts, following current recommendations (Höhne et al., 2022; Price et al., 2008; Via et al., 2014).

2.5.1. Evaluations

Within the evaluation^{pre}, evaluation^{inter}, and evaluation^{post}, various topics were queried using multiple items. These included 'personal data', 'previous experience', 'user behaviour', 'motivation', 'learning objectives', 'subjective assessment of competence', 'teaching material', and 'course evaluation'. The answers were collected using a seven-point Likert scale (1 = strongly disagree; 7 = strongly agree) or dichotomous questions (yes/no), as well as free text fields. Sociodemographic data such as age and gender were collected to describe the study population. However, these data were not included in the statistical evaluation of outcomes. Motivation and self-efficacy were measured using self-developed items based on prior studies and expert consensus. Although not part of a validated psychometric tool, the items were designed to reflect established constructs in medical education. The learning objectives, which were predefined by the course organizers in accordance with national ultrasound education guidelines, were evaluated by asking students to rate how well they understood and achieved them before and after the course.

2.5.2. Theory Test

The written learning success tests (max. 94 points theorypre + theoryinter T1–T2 and max. 100 points in theorypost) examined the following areas of competence: 'anatomy' (max. 11 points); 'basics' (max. 29 points); 'assignment tasks' (max. 6 points); 'normal findings/structure recognition in orientation sections' (48 points); and 'pathology (recognition)' (max. 6 points, only T3). These competences were defined in the learning objectives. The main question types used were labelling questions, gap-filling questions, and single-choice questions (Puthiaparampil & Rahman, 2020). Each test took 30 min to complete.

2.5.3. Practical Examinations

To assess the participants' practical competences, direct observation of procedural skills (DOPS) examinations were designed and implemented in accordance with preliminary studies (J. M. Weimer et al., 2023a) and with consideration of the objective structured assessment of ultrasound skill scale (Tolsgaard et al., 2013) (Supplement S8). The developed

DOPS each consisted of a case vignette and examined the following competence areas: 'patient guidance', 'transducer handling', 'examination procedure', 'image explanation', 'measurement', 'interpretation', and 'overall performance'. The $DOPS^{inter}$ used at time T2 (56 points) was completed by all participants, whereas at T3, 3 out of 6 possible $DOPS^{post}$ (max. 147 points) were completed per participant.

$DOPS^{inter}$ examined all ultrasound views (parasternal, apical, subxiphoid) with a total of 4 standard views (SC4C, A4C, PLAX, PSAX). The apical five-chamber view (A5C) and the suxiphoid vena cava incision (SCVCI) were also integrated into $DOPS^{post}$ 1–6. For each case vignette, two ultrasound positions with a total of two standard views and an additional transfer task on further diagnostic and therapeutic procedures for the case were tested.

2.5.4. Statistical Analysis

For this study, a power analysis was performed to determine the sample size required to detect a statistically significant effect. Based on an expected effect size of 0.6, a significance level of 0.05, and a desired power of 0.80, the calculated sample size was set at 68 participants (34 in each group). Data collection was carried out using the survey and test tool LimeSurvey (LimeSurvey GmbH, Hamburg, Germany), written questionnaires, and practice exam sheets. All data were saved with Microsoft Excel. All statistical analyses were performed in Rstudio (Rstudio Team [2020]. Rstudio: Integrated Development for R. Rstudio, PBC, http://www.rstudio.com, last accessed on 20 April 2024) with R 4.0.3 (A Language and Environment for Statistical Computing, R Foundation for Statistical Computing, http://www.R-project.org; last accessed on 20 April 2024). Where possible, a main scale score was derived from the average of the subscale scores. The internal consistency of the scales was tested and ensured by calculating the reliability according to Cronbach's alpha. Binary and categorical baseline variables are given as absolute numbers and percentages. Continuous data are given as medians and interquartile range (IQR) or as means and standard deviation (SD). Categorical variables were compared using a chi-squared test and continuous variables using a T-test or the Mann–Whitney U test. These tests were also used to calculate the influence of the factors on the subjective and objective results. In addition, parametric or non-parametric (Kruskal–Wallis) analyses of variance (ANOVAs) were calculated and further explored with pairwise post hoc tests (*t*-test or Mann-Whitney U). Furthermore, pairwise correlations (using Spearman's rank correlation coefficient) were obtained, and the correlation effect sizes and significances were calculated for both groups. *p*-values < 0.05 were considered statistically significant.

3. Results

3.1. Data Description

The reliability tests, according to Cronbach's alpha, showed that the internal consistency of the main scales, in a range of 0.8–0.9, did not vary considerably.

3.2. Baseline Characteristics of the Study and Control Group

A total of 109 datasets (Figure 2) were included in the statistical analysis (n = 52, study group; n = 57, control group).

The demographic characteristics and educational profiles of the study and control groups were approximately equivalent (see Table 1). Both groups had a similar mean age (study: 25.6 ± 3.5 years vs. control: 25.0 ± 3.6 years; $p = 0.21$), were mainly female (study: 62% vs. control: 58%; $p = 0.61$), and had largely already seen echocardiography (study: 83% vs. control: 83%; $p = 0.46$). A large proportion of both groups had already attended an abdominal sonography course (study: 35% vs. control: 40%; $p = 0.68$) and had performed an echocardiography (study: 48% vs. control: 58%; $p = 0.27$).

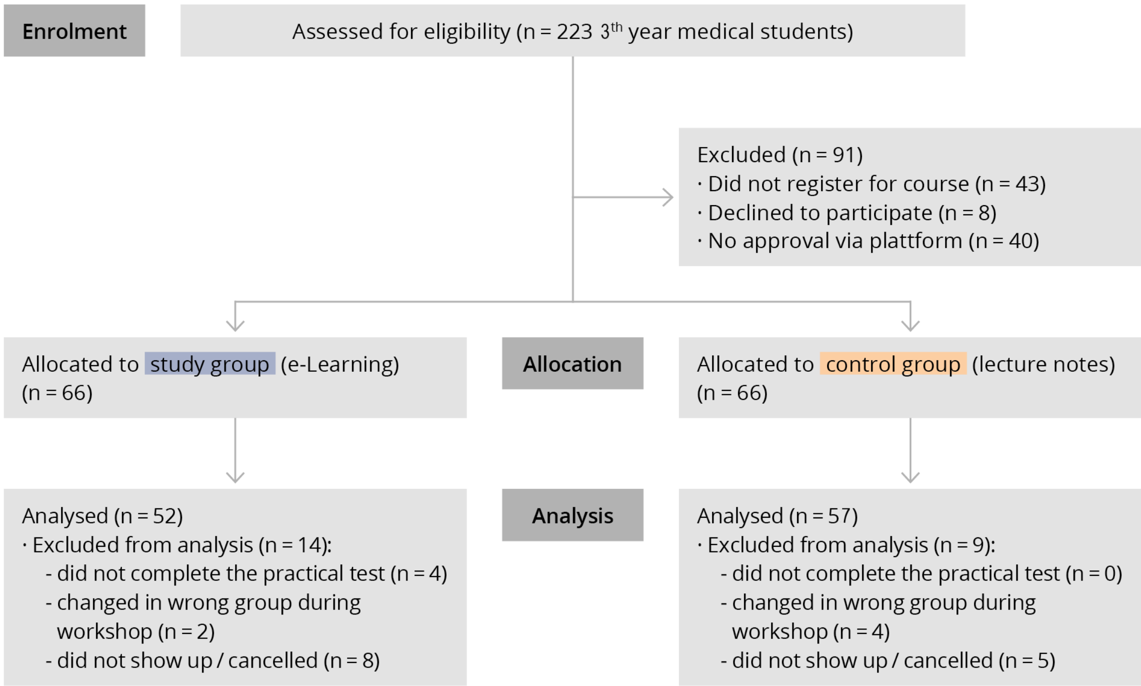

Figure 2. Flow diagram showing participant recruitment and data analysis according to CONSORT guidelines.

Table 1. Baseline characteristics of the participants of the control group (lecture notes) and study group (e-learning).

Items	**Study Group n = 52**	**Control Group n = 57**	***p*-Value**
T1			
Age	25.6 ± 3.5	25.0 ± 3.6	0.21
Gender			0.61
Female	32	33	
Male	20	23	
N/A	0	1	
Vocational training in the medical sector before studies			0.43
Yes	34	32	
No	18	25	
Experience with ultrasound			0.38
Yes	30	27	
No	22	30	
Experience with CT			
Yes	18	14	0.35
No	34	43	
Experience with MRT			
Yes	16	14	0.61
No	36	43	

Table 1. *Cont.*

Items	**Study Group n = 52**	**Control Group n = 57**	***p*-Value**
Experience of interpretation of cross-sectional images			
Yes	18	16	0.6
No	34	41	
Previous participation in abdominal ultrasound course			0.68
No	34	34	
Yes	18	23	
Time frame:			
1 = <10 TU	16	20	0.5
2 = 10–20 TU	2	3	
3 = >20 TU	0	1	
Observed/performed ultrasound			
abdomen	38	44	0.78
head-neck	12	19	0.33
punctures	21	17	0.34
Observed an echocardiography			0.46
No	9	10	
Yes	43	47	
Time frame:			
1 = <10 examinations	34	37	0.3
2 = 10–20 examinations	4	6	
3 = 20–50 examinations	5	2	
4 = >50 examinations	0	2	
Performed an echocardiography			0.27
No	27	24	
Yes	25	33	
Quantity			
1: <10	25	31	0.13
2: 20–50	0	2	
T2			
To what extent did you use the teaching material provided to prepare for the ultrasound course?			0.2
1–2 h	6	11	
2.5–4 h	29	35	
4.5–6 h	15	10	
6.5–8 h	2	0	
8.5–10 h	0	1	
Have you had any practical training in echocardiography since receiving the educational media?			0.01
Yes	20	8	
No	32	49	

3.3. Motivation, Course Concept, Teaching Materials, and Learning Objectives

Supplement S9 and Figure 3a list the evaluation results of motivation and of the course concept, including the learning materials used and the learning objectives set and achieved.

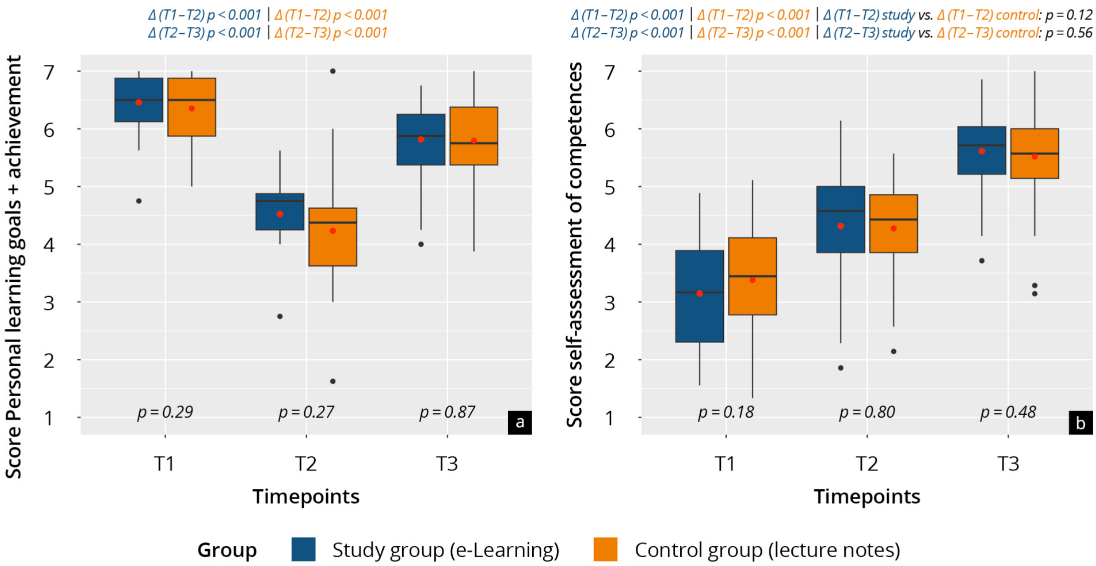

Figure 3. Results of the survey regarding the motivation and learning objectives (**a**) and subjective competence development (**b**) at time points T1, T2, and T3 in the total score of the study group (blue) and control group (orange).

The motivation to participate in the course and the use of the teaching materials after the course remained at a consistently positive level from T1 (control 6.4 ± 0.8 vs. study 6.6 ± 0.6; p = 0.22) to T3 (control 6.4 ± 0.8 vs. study 6.4 ± 0.7; p = 0.93) with no significant differences between the groups. The participants also stated at T1 that their well-prepared lecture notes (control 6.1 ± 0.8 vs. study 6.1 ± 0.8; p = 0.95) and e-learning (control 6.0 ± 1.1 vs. study 5.6 ± 1.4; p = 0.34) or the combination of both (control 6.1 ± 1.0 vs. study 5.9 ± 1.3; p = 0.56) motivated them to attend or prepare for a course. According to the participants, the visual design of a learning medium influences the motivation to use it (control 6.5 ± 0.8 vs. study 6.3 ± 0.8; p = 0.16).

The course curriculum was rated positively by both groups in all the items surveyed (scale point ranges between 5.7 and 6.9), with no significant differences between the groups. Both groups (control 39% vs. study 44%; p = 0.17) expressed a wish for more accompanying lectures, particularly in the area of 'pathologies'. In addition, the two groups supported the integration of echocardiography within their medical studies (control 6.9 ± 0.5 vs. study 7.0 ± 0.2; p = 0.40).

According to the participants, the learning objectives set and assessed at the beginning (T1) (control 6.4 ± 0.6 vs. study 6.5 ± 0.5; p = 0.30) could not be fully (p < 0.001) achieved after the preparation (T2) (control 4.2 ± 0.9 vs. study 4.5 ± 0.8; p = 0.30). At the end of the course (T3), the assessment of the achievement of the learning objectives (control 5.8 ± 0.7 vs. study 5.8 ± 0.6; p = 0.9) was higher compared to the preparation phase (p < 0.001), although the subjective learning objectives were not fully achieved overall (T1–T3 for both groups p < 0.001)

Both groups rated their learning medium highly positively after the preparation period (T2) in all items surveyed (control mean 5.0–06.5 scale points vs. study mean 5.1–6.6 scale points) without significant differences in the overall score (control 5.7 ± 0.8 vs. study 5.7 ± 1.0; p = 0.74) and all sub-items queried.

3.4. Development of Subjective Competence

The results of the subjective assessment of competence are shown in Figure 3b and Supplement S10. No significant differences between the groups were found in the overall scores at any of the three time points. In both groups, a continuous and significant (delta

$p < 0.001$) increase in subjective competence was observed in the overall score as well as in almost all sub-items surveyed during the preparation period (T1–T2) and face-to-face course period (T2–T3). The assessment of skills within the 'transducer handling', 'visual perception', and 'spatial orientation' competence areas did not improve significantly from T1 to T2 ($p \geq 0.05$), but did improve from T2 to T3 ($p < 0.01$) in both groups.

3.5. Development of Objective Competences

3.5.1. Theory

The results of the theory test are presented in Figure 4. Both groups achieved results in similarly high ranges at all three time points without significant differences. A continuous and significant (delta $p < 0.001$) increase in test performance was measured in both groups over the course of the preparation period (T1–T2) and the attendance course period (T2–T3) in the overall score and all subcategories tested except 'anatomy'. With regard to the pathologies tested in T3, no significant differences were found between the groups (study: 2.8 ± 1.4 vs. control: 2.6 ± 1.1; $p = 0.44$), whereby the results were most inferior in comparison to the other categories tested ($p < 0.05$).

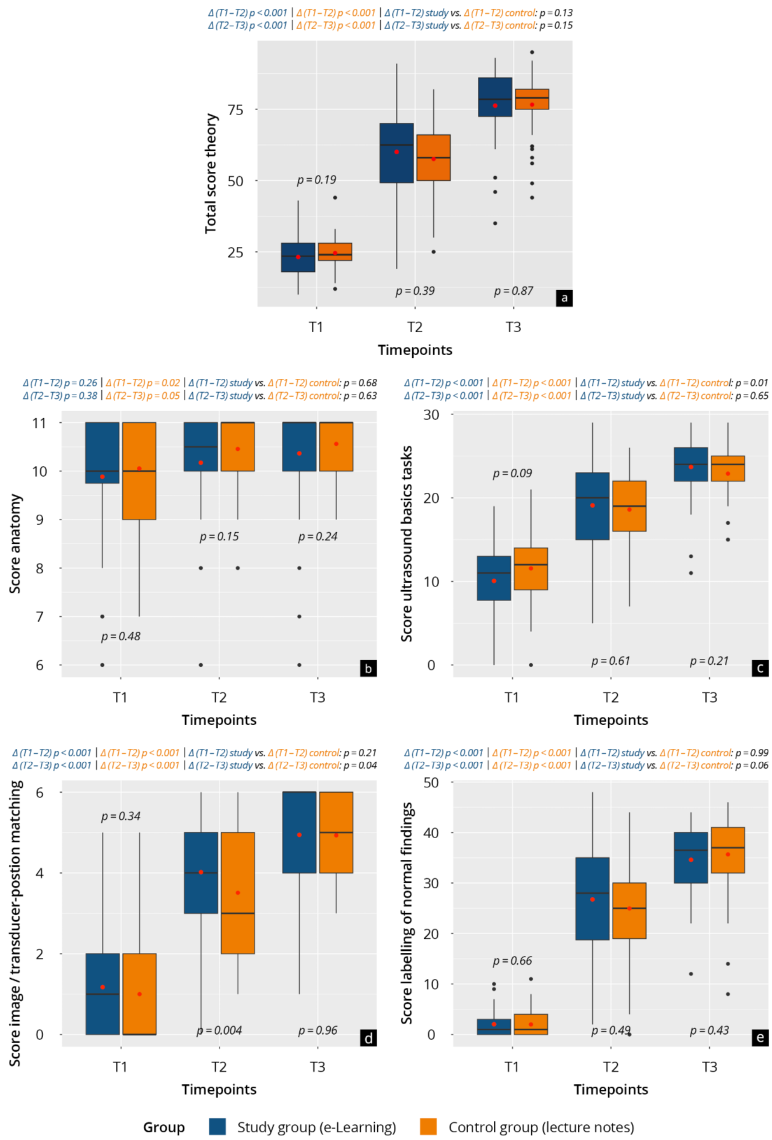

Figure 4. Results of the theoretical test at T1, T2, and T3 in the total score (**a**) and the subcategories of anatomy tasks (**b**), ultrasound basics tasks (**c**), image/transducer position-matching (**d**), and labelling tasks for normal findings (**e**) of the study group (blue) and control group (orange).

3.5.2. Direct Observation of Procedural Skills (DOPS) Tests—Results

The results of the practical tests at T2 and T3 are shown in Figure 5. After the preparation phase, the study group (54.2 ± 17.1%) had significantly ($p = 0.03$) higher scores in practical competences than the control group (47.5 ± 14.2%). At the end of the course, the overall practical competences in both groups were significantly higher than at T2 (delta $p < 0.001$) at a similarly high level (study 72.5 ± 8.8% vs. control 74.52 ± 11.9%, $p = 0.31$). This also pertains to the individual results of the DOPS, where no significant differences were found between the two groups.

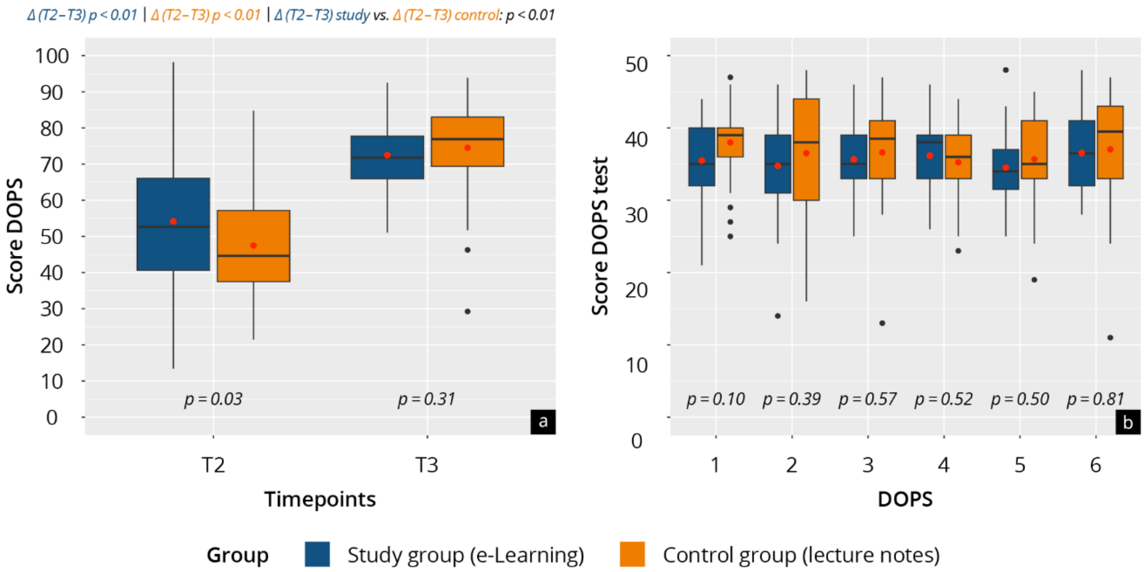

Figure 5. Results of the practical test of the study group (blue) and control group (orange) at time points T2 and T3 of the total score DOPS (**a**) and for each individual DOPS test (**b**).

3.5.3. Influencing Factors and Correlations

The analysis of the potential factors influencing the subjective assessment of competence and objective test results are listed in Supplement S11. In particular, 'already performed echocardiography independently', 'ultrasound courses already completed', 'experience with ultrasound', 'practical training before the course', and 'use of teaching materials > 4 h' had a significant ($p < 0.05$) positive influence on the objective test results.

3.5.4. Correlations

At T2, the overall results of the theory test in both the control group (r = 0.3; $p = 0.03$) and the study group (r = 0.35; $p = 0.01$) correlated moderately strongly with the self-assessment of skills. There was a strong correlation between the overall results of the theory test and the overall results of the practical tests in the study group (r = 0.51; $p < 0.001$), which was not found in the control group (r = 0.01; $p = 0.9$).

4. Discussion

The growing importance of e-learning and other digital teaching materials in medical ultrasound education—particularly following the accelerated changes during the COVID-19 pandemic and the inherent complexity of cardiac imaging—highlights the significance of this study (Blank et al., 2022; Johri et al., 2018; Stoehr et al., 2021).

This research investigated the effectiveness of digital teaching resources compared to traditional analogue materials within a flipped classroom framework, specifically for training in focused cardiac ultrasound (FoCUS). Given that the goal of medical education, particularly in ultrasound training, is to effectively convey both theoretical knowledge and practical skills, this comparison is especially relevant (Dieden et al., 2019).

The study reveals that the group using e-learning resources developed comparable competences in both theoretical and practical training to the group using analogue lecture notes. Remarkably, this was accomplished with reduced preparation time and fewer practical sessions, emphasising the efficiency of digital learning methods. Both groups exhibited high motivation and positive attitudes toward the use of digital teaching media in ultrasound education. These outcomes, which reflect those in preliminary studies (Haskins et al., 2018; J. M. Weimer et al., 2024), suggest that e-learning can serve as a valuable complement or even an alternative to traditional analogue teaching materials in ultrasound training, potentially offering greater efficiency in certain contexts. Consequently, the study provides a solid foundation for discussing the integration of e-learning into medical training programmes, particularly within ultrasound education, and explores the potential for future certification of such modules (Blank et al., 2022; Werdan et al., 2020).

Current learners have a strong propensity to use web- and social media-based curricula (Johri et al., 2018). This study reinforces the notion that both analogue and digital teaching materials can effectively develop competences within a flipped classroom concept. This is consistent with prior research in FoCUS and broader sonography training, where both subjective and objective competences have been successfully cultivated through these methods (Canty et al., 2019; Chiem et al., 2016; Harel-Sterling, 2023; Haskins et al., 2018; Khoury et al., 2020; Shehata et al., 2022; Torabi et al., 2021; J. M. Weimer et al., 2024). E-learning in particular offers advantages in theoretical preparation by allowing learners to progress at their own pace and deepen their understanding of complex content through repeated interactions with the material (Blank et al., 2022; Elshami et al., 2022; Ruiz et al., 2006). This approach is especially beneficial for grasping intricate sonoanatomy and enhancing spatial visualisation, both critical in FoCUS and general sonography (Harel-Sterling, 2023; Lien et al., 2023).

Despite having less practical time, the e-learning group achieved a competence level comparable to that of the control group, further highlighting the potential of digital learning approaches to prepare students for practical exercises through training videos (Altersberger et al., 2019; Situ-LaCasse et al., 2021).

However, it is important to note that in practical training, where skills such as probe handling and ultrasound image interpretation are crucial, physical presence and direct instructor guidance remain indispensable. Future training models should thus adopt blended learning when integrating e-learning, as supported by the positive reception of the blended learning, flipped classroom approach that was observed in this study and previous research (Blackstock et al., 2015; Jujo et al., 2022).

The study also identified several influencing factors, notably the significant positive impact of ultrasound or echocardiography experience on objective test results. This finding may indicate that even a basic level of prior knowledge in imaging techniques can support skill development in advanced applications such as echocardiography. While this cannot be conclusively established from the present short-format course, it aligns with existing literature suggesting that early practical exposure may help accelerate the learning process (Cawthorn et al., 2014; Chisholm et al., 2013; Harel-Sterling, 2023). Moreover, the study found that extended use of teaching materials (over four hours) significantly improved test outcomes, suggesting that the intensity of self-directed study is crucial for competence development. This observation may reflect aspects of autonomous motivation, as described in self-determination theory (Ryan & Deci, 2000), where learners who take responsibility for their learning tend to show increased engagement and cognitive depth (Ryan & Deci, 2000). However, this interpretation should be viewed cautiously, given the exploratory nature of the study. Future research could further explore how the structure and content of e-learning materials can be optimised to enhance learning outcomes.

The study also examined the motivation and attitudes of learners toward digital teaching, finding that both are critical to the success of e-learning initiatives, in line with previous studies (Kusurkar et al., 2011; Lin et al., 2017). The high acceptance of e-learning in medical education, particularly when well-structured and technically sound, was evident across both the e-learning and analogue groups. Participants reported high satisfaction with the provided materials and expressed a positive attitude toward the use of digital resources in preparing for practical courses. The visual design of learning materials was noted as an important factor influencing motivation, underscoring the need for user-friendly design in both digital and analogue teaching resources, which can be confirmed by preliminary studies (Mahdavi Ardestani et al., 2023; Reyna, 2013; J. M. Weimer et al., 2024).

Looking to the future, the study suggests that digital teaching, particularly e-learning, holds significant promise for medical education. By enabling flexible, self-directed learning that complements traditional methods, e-learning can enhance the effectiveness and efficiency of educational programmes while still ensuring the necessary practical skills are taught through in-person instruction (Blank et al., 2022; D. Hempel et al., 2016). The integration of e-learning modules into existing training programmes could provide a scalable and flexible solution to extend the reach and efficacy of medical education (Hoppmann et al., 2022; Ruiz et al., 2006).

E-learning could be pivotal in filling training gaps and optimising educational resources to address the growing demand for qualified healthcare professionals. Future developments in e-learning may include interactive and adaptive technologies such as virtual reality, augmented reality, or artificial intelligence to facilitate personalised learning pathways tailored to individual progress and needs. While these tools hold promise, further research is needed to evaluate their effectiveness in ultrasound education (Beaulieu et al., 2015; Canty et al., 2019; Gat et al., 2024; Weber et al., 2019; Daum et al., 2024).

As digital teaching formats continue to gain importance, questions of standardisation and integration into formal curricula are becoming increasingly relevant.

The results of this study demonstrate that e-learning formats can achieve educational outcomes equivalent to traditional methods within a structured training environment. These findings underscore the relevance of including digital modules in future quality assurance and certification frameworks, particularly in the context of competence-based ultrasound education, where flexibility and scalability are increasingly critical. Currently, the certification of such modules poses challenges, but establishing standardised quality criteria for e-learning offerings could ensure they meet the rigorous standards of medical education. Certified e-learning programmes accredited by recognised professional societies could assure learners that the content aligns with current scientific and practical standards, thereby promoting their adoption in clinical practice. Certified e-learning modules could also gain formal recognition within continuing medical education, enhancing learners' professional qualifications. Establishing such certifications would not only improve the quality of medical education but also advance the digital transformation of the field (Blank et al., 2022; A. M. Weimer et al., 2023; Werdan et al., 2020).

Finally, while this study demonstrates that e-learning can effectively improve theoretical and practical skills in the short term, further research is needed to explore the long-term impact of these skills on clinical practice (Cosyns et al., 2015; Harel-Sterling, 2023; Parra et al., 2024; J. M. Weimer et al., 2023b). Understanding how well these competences are applied and sustained in real-world clinical settings will be crucial in assessing the lasting value of e-learning in medical education.

Limitations

While providing valuable insights into the effectiveness of digital versus analogue teaching resources in a flipped classroom setting for FoCUS training, this study has several limitations that must be acknowledged. Firstly, the study was conducted at a single centre, which may limit the generalizability of the findings. The results may not be fully applicable to other institutions or educational settings, especially those with different student demographics, resources, or instructional methodologies. The university hospital at which the study was conducted is a well-resourced academic centre with robust digital infrastructure and students who are experienced in engaging with online learning environments. In this context, digital literacy could be higher than average. This assumption is supported by findings from the DigiMed study, which demonstrated that medical students in Germany—particularly during and after the COVID-19 pandemic—developed substantial competence and confidence in digital learning environments (Stoehr et al., 2021). As such, the success of the e-learning intervention in this study may in part reflect the existing digital readiness of the participants.

Secondly, the study was confined to a specific educational context: FoCUS training for undergraduate medical students. Therefore, the findings may not be directly transferable to other areas of medical education or ultrasound training, where different competences and learning objectives might necessitate alternative teaching approaches.

Another limitation is related to the practical examination environment. The hands-on assessments were conducted in a controlled educational setting, which might not accurately reflect the complexities and challenges of real-world clinical scenarios. This controlled environment may have contributed to higher performance levels that may not necessarily translate to clinical practice.

It should be noted that the 15% reduction in practice time for the e-learning group was an intentionally introduced, artificial condition designed to assess the potential efficiency of digital preparation. However, this reduction does not necessarily reflect real-world teaching scenarios and may have influenced the overall competence development. It also remains unclear whether comparable outcomes would have been observed if both groups had received equal amounts of practical training. Additionally, differences in how participants engaged with the respective learning media—such as intensity, frequency of repetition, or individual learning strategies—were not controlled and should be considered when interpreting the results. A further limitation of this study is the voluntary nature of participation, which likely introduced self-selection bias toward particularly motivated students. This may restrict the generalizability of results, especially regarding motivation, satisfaction, and performance. Additionally, the reliance on self-reported measures for assessing motivation, competence, and satisfaction entails an inherent risk of subjective bias. These responses may be influenced by factors such as digital affinity or a generally positive attitude toward technology, rather than reflecting actual learning outcomes. Such potential response biases should be carefully considered when interpreting the findings, particularly in the context of digital learning environments. Lastly, while the study employed a range of subjective and objective measures to assess competence development, there is an inherent limitation in self-reported data, which can be influenced by various biases. Future research should consider a more diverse and multicentre approach, including long-term follow-up to better assess the sustainability and real-world applicability of the competences gained through different teaching methods.

5. Conclusions

This study suggests that e-learning is a viable method for content delivery in flipped classroom settings, producing similar outcomes to traditional methods in this specific context despite reduced practice time. Both e-learning and analogue lecture notes facilitated significant improvements in theoretical knowledge and practical skills among undergraduate medical students, with high levels of student motivation and satisfaction reported across both groups. The findings highlight the potential of e-learning as a viable and efficient alternative to traditional teaching methods, particularly in the context of modern medical education, where flexibility and resource optimisation are increasingly important.

However, the study also underscores the necessity of maintaining practical, hands-on training under direct instructor supervision to ensure the full development of ultrasound competences. Given the controlled environment in which practical assessments were conducted, further research is needed to evaluate the long-term retention of skills and their application in clinical practice. Additionally, the study's single-centre design suggests that further multicentre studies are warranted to validate these findings across diverse educational settings.

Overall, this research supports the integration of e-learning into ultrasound education as part of a blended learning approach, which could enhance the scalability and accessibility of medical training. Future efforts should focus on standardising e-learning modules and exploring their certification to ensure quality and consistency in medical education programmes globally.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/educsci15070810/s1. Supplementary Materials S1: Course sequence, adapted from Greim et al. and Weimer et al.; Supplementary Materials S2: Learning objectives in the FoCUS course model developed and adapted from Greim et al. and Weimer et al.; Supplementary Materials S3: Content structure of e-learning; Supplementary Materials S4: Example of flashcards and functions of e-learning part 1; Supplementary Materials S5: Example of flashcards and functions of e-learning part 2; Supplementary Materials S6: Sample questions from the theory tests in the 'Basic' competence area; Supplementary Materials S7: Sample questions from the theory tests in the 'assignment tasks' and 'normal findings/structure recognition in orientation sections' competence areas; Supplementary Materials S8: Example sheet of the FoCUS DOPS; Supplementary Materials S9: Results of the differentiated consideration of motivation, learning objectives, course evaluation, and teaching materials; Supplementary Materials S10: Results of the subjective self-assessment of competences at time points T1–T3; Supplementary Materials S11: Results of the analyses of the influence of possible factors on the subjective assessment of competence and objective test results.

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Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The data presented in this study are available on request from the corresponding author. The data are not publicly available because of institutional and national data policy restrictions imposed by the ethics committee, since the data contain information that could potentially identify study participants. Data are available upon request (contact via weimer@uni-mainz.de) for researchers who meet the criteria for access to confidential data (please provide the manuscript title with your inquiry).

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