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Spiral-curricular blended learning for the mathematics education in physics teacher training courses

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A good physics education depends on a good, transferable mathematics education. A concept for a cross-modular blended learning math course developed for the first two semesters of our physics teacher trainee study program is introduced. The course covers the important new mathematics required for the development of the conceptual understanding of the classical experimental physics mechanics and electrodynamics. It is based on three pillars: parallelism of the math topics to the physics lectures, spiral-curricularity to prior knowledge and high quality digitally available interactive materials such as interactive videos, formative tests and exercises to foster a self-regulated learning of the students in online as well as face-to-face learning environments. The blended learning math course and its face-to-face math seminars are integrated into the experimental physics modules. Results of surveys among the first two cohorts of course participants indicate that the design of the math course is well accepted and the interactive videos are very well received by the students. Initial tests on the learning effectiveness indicate a sufficient development of long term knowledge by the students.

KEYWORDS

flipped classroom, mathematical methods, blended learning, interactive explanatory videos, self-regulated learning, higher education in mathematics, higher education in physics

1 Introduction

In the introductory phase of engineering, science and science teacher training courses at universities and colleges, students are faced with the challenge of gradually developing their own study skills. In particular, they have to learn the transition from predominantly inductive, externally controlled learning methods at school to deductive and self-regulated teaching methods at universities (Fischer, 2014; Quinn and Aarão, 2020). This transition is particularly difficult because the requirements for applicable and retrievable mathematical skills in these courses of study very quickly exceed the level acquired in the previous school education. Some authors speak of a real math shock at the beginning of the course (Bausch et al., 2014; Lumpe, 2019; Schild, 2021). Therefore, many universities offer separate mathematics courses to develop the mathematical skills of the students in parallel to the respective basic engineering and science courses. However, the transfer of calculation strategies learned in separate mathematics modules to their application in science is difficult and too often fails (Dunn and Barbanel, 2000). It is therefore advisable, especially in the introductory phase of studies, to dovetail the training in mathematics closely with the respective engineering or natural sciences.

In addition, a didactic concept for the entire introductory phase is necessary in order to accompany students with their heterogeneous learning requirements as they take the step into self-organized university learning (Fischer, 2014; Pilotto, 2021; Kaps and Stallmach, 2022; Kämpf and Stallmach, 2023). The expected heterogeneity of the students can be addressed if blended learning concepts are implemented. Users of such courses are able to adapt their learning speed, their learning time, the necessary repetitions and the materials used for learning to their own learning strategy (Diekjürgen and Minah, 2021; Finkenberg, 2018; Volk, 2020; Bitzenbauer and Hennig, 2023; Nouri, 2016). Teachers thus support the development of their students' self-regulated learning skills.

In this paper we present a spiral-curricular blended learning approach for the mathematical education of our teacher training courses in physics that we firstly implemented in winter term 2022/23 and in summer term 2023. The blended learning course is integrated in the first two modules of the experimental physics education. It is adapted to the mathematical requirements of these basic physics lectures. We describe the contents of our cross-module mathematics course for the first two semesters and explain how the knowledge is transferred in interactive videos and how it is consolidated and expanded by means of in-depth face-to-face seminars as well as formative tests and accompanying recitations (Kämpf and Stallmach, 2023). Using the learning sequences to the calculus of complex numbers, which are introduced in physics for the description of mechanical oscillations during the first semester and are used and extended during the second semester for the complex alternating current calculation, we discuss first results on the learning effectiveness and the establishment of an applicable long-term knowledge through our concept of an integrated spiral-curricular mathematics education. In addition to these first studies on the learning effectiveness we evaluated the quality of the course design by surveys. The purpose of this investigations is the research-based assessment and future improvement of our new blended learning mathematics course concept.

2 Design of the cross-modular blended learning mathematics education

2.1 Integration of the mathematical methods seminar in the physics course

The teacher training programs at most universities in Germany require the simultaneous education of students in two different sciences which the students may freely chose and which will become their two main teaching subjects as future teachers at secondary or extended secondary schools. Additionally, all teacher trainees have to enroll in educational theory (pedagogical) training which is aimed to develop their teaching skills. At Leipzig University these three pillars of the teacher training start simultaneously with the beginning of the study. Moreover, the study regulations establish an equal distribution of credit points and thus study time between these three pillars especially during the initial 2 years of the study (see Table 1). Only about half of the physics teacher trainees choose mathematics as their second

teaching subject (Woitzik et al., 2023). Hence the other half of the physics teacher trainees experience no basic mathematical education during their whole study. However, mathematics is the language of physics and there is no doubt that significant more mathematical concepts than taught at school have to be understood in order to develop the necessary competences to understand the basic concepts of physics, to successfully complete the physics teacher training and to become a respected physics teacher.

To address this situation it was decided to separate teacher training courses and the bachelor of science courses for the basic experimental physics education traditionally taught at the very beginning of physics study programs for future teachers and scientists, respectively. This opened space to tailor the courses for physics teacher trainees to better meet the requirements regarding the subject education in physics and mathematics. However, the strict division of credit points between physics, the second teaching subject and educational theory science (Universität Leipzig, 2018) limits this freedom with regard to the scope of courses for physics and the necessary mathematics training. Therefore, the decision was made to integrate the mathematical training into the experimental physics modules of the first two semesters of the physics teacher training courses by accompanying seminars with a focus on the necessary mathematical methods (Mathematical Methods called MaMe in the following, see Table 1).

As Dunn and Barbanel (2000) showed for a an integrated math/physics course focusing on electricity and magnetism, such an interleaved teaching makes the mathematical topics relevant to the students, connectable to physics problems, and promotes thinking through both the mathematical and physics learning content. Additionally, one may expect that the extraneous cognitive load for the learners can be reduced, if a consistent notation and language is applied in all materials handed out to the students and used by the teaching stuff in the physics lectures, recitations and MaMe seminars (Tindall-Ford et al., 2019).

Moreover, a close integration of the MaMe seminars into the physics courses offers the potential to treat important mathematical concepts and their application to solve physics problems in parallel. Table 2 displays our general concept when to treat math and the corresponding physics topics throughout the first year of the physics teacher trainee courses. The order of topics for the two lectures per week in both experimental physics modules (mechanics EP 1 and electrodynamics EP 2) determine the topics treated during the corresponding integrated MaMe seminars (Kaps et al., 2020). Throughout the two physics courses, the mathematics, which is necessary for the just introduced physics content, is developed step wise under consideration of spiral-curricular aspects.

2.2 Teaching mathematical methods in a blended learning format

In order to better accompany and structure the studies for the physics teacher trainees during the first two semesters, the interleaved math education has been gradually transferred into a blended learning format since the winter term 2022/2023. Figure 1 illustrates the general structure of our math education concept. It consists of the acquisition of the necessary knowledge in a

TABLE 1 Curriculum and distribution of credit points during the first year of the physics teacher training program at Leipzig University.

Physics			2nd teaching subject	Educational science	
Mechanics (EP1)			Courses 1st semester	Educational sciences 1	
10 CP			10 CP	10 CP	
Lecture	Recitation	MaMe			
Electrodynamics (EP2)			Courses 2nd semester	Educational sciences 2	Supplementary studies
10 CP			10 CP	5 CP	5 CP
Lecture	Recitation	MaMe			

The mathematical methods seminars are integrated into the experimental physics modules 1 and 2 taught during subsequent winter (1st semester) and summer terms (2nd semester), respectively.

TABLE 2 Integration of mathematical methods seminars into the two subsequent experimental physics modules EP1 and EP2.

Topic list of the MaMe seminars associated to the mechanics and electrodynamics lecture			
Mechanics EP1	MaMe 1	Electrodynamics EP2	MaMe 2
Introduction	Introduction to the MaMe course and The Smart Physics Laboratory	Introduction	Functions of several variables
Mechanics of a point mass	Functions and vectors to describe physical laws and trajectory curves	Electrical field of point charges	Cartesian, cylindrical and spherical rotation coordinates system
Newton's axioms and conservation of energy	Introduction to differential equations and separation of variables	The electrical field and the potential of point charges—energy conservation	The differential operators div and Δ
Equation of motion of a particle in non-constant force fields	Integration by parts and substitution	Electrical fields of charge distributions and the electric flux density	Surface integrals and Gauss's Divergence Theorem
Systems of point masses and conservation of momentum	Volume integral and center of mass	The electrostatic field distributions and its forces in capacitors	Line integrals to calculate potential inside a capacitor
Rotational motion of a rigid body	Moments of inertia of a system of particles	DC networks with ohmic and capacitive resistors and Kirchhoff's rules	Inhomogeneous differential equation describing the charge curve in an RC circuit
Mechanical oscillations	Introduction of complex numbers to describe harmonic oscillation	The magnetic field of an arbitrary distribution of electric currents; Biot–Savart law	Understanding and application of the Biot–Savart law
Free, damped and forced oscillator	Ordinary linear differential equation and their solution for the damped oscillator	Faraday's law of induction and Lenz's rule	Stokes' theorem to transfer Maxwell's 3rd and 4th equation
Mechanics of deformable solids and fluids	Taylor and Laurent series	AC networks with complex resistors; phasor diagrams	Deepening complex numbers: complex resistors to describe ac circuits
Gravity as a conservative force field	Introduction to vector analysis and differential operators gradient and curl	Open oscillating circuits; Hertzian dipole	Summary of the course content

The table shows the chapter headline of the physics lectures and recitations and the math topic treated during the corresponding MaMe seminars.

first self-study phase, common transfer via the face-to-face MaMe seminars and an independent application to solve physics task again as self-study. Thus, our interleaved MaMe education represents a flipped classroom teaching-learning concept applying blended learning methods.

2.2.1 Self-study for the acquisition of basic knowledge

The materials for the first self-study phase are interactive explanatory videos and formative tests such as task and quizzes. We also recommend our students literature sources, which are generally math text books. For each of these main math topics (see Table 2) which are discussed during

the corresponding face-to-face seminars we produced two interactive videos explaining the basics of the mathematics and its application in physics. After important statements in the videos, students may test their own understanding by solving formative interactive tasks. Students receive feedback on how to proceed on their personal learning path during this first acquisition of knowledge.

2.2.2 Common transfer during the face-to-face MaMe seminar

During the following face-to-face MaMe seminar the acquired knowledge will be deepened and transferred to further applications to physics. The seminar presents a common practice space
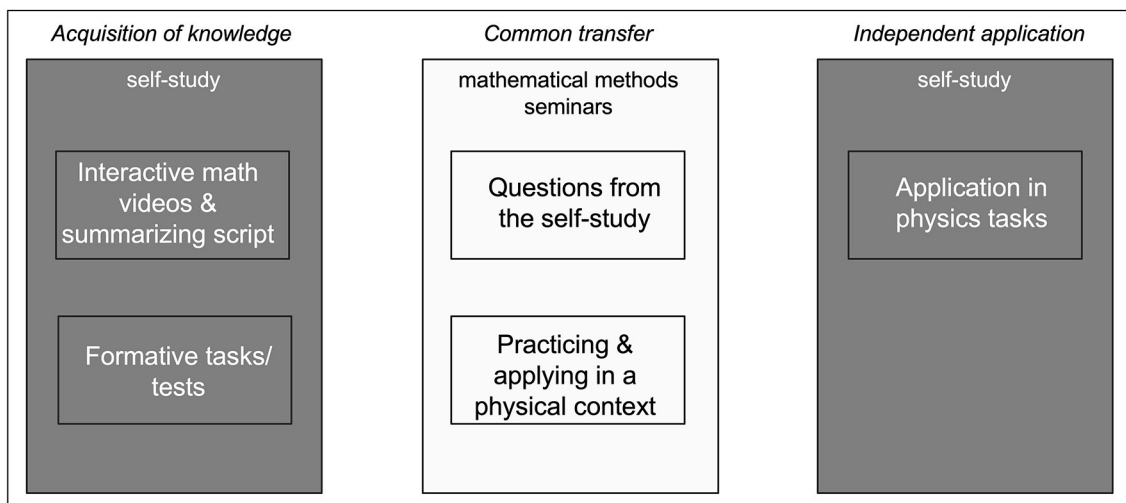
FIGURE 1
Blended learning concept for the interleaved mathematics education. The three columns show the main teaching elements utilized. Each of the math topics (see Table 3) is covered via two self-study phases and a face-to-phase MaMe seminar.

where the transfer of knowledge is guided by the teaching stuff (see Figure 1). The teachers prepare these in-depth face-to-face classroom seminar with the information on the level of understanding and knowledge from the anonymous formative tests of the first self-study phase. The seminar begins with a question and answer session about difficulties of the self-study phase. In order to activate the students and to recall the processed topics, this is supported with a few short questions on the contents of the videos. Afterwards, all questions that do not require repeating the video are answered.

The focus of the face-to-face MaMe seminar is on practicing and transferring the mathematical framework to relevant physical applications. During the seminar physical phenomena are described mathematically, which were just addressed during experimental physics lecture. This will illustrate the relevance of mathematics and improves the transferability of the language of science to physics. In working through various tasks, students become increasingly independent and the teacher takes on the role of a learning guide and mentor while the seminar progresses (Finkenberg, 2018).

2.2.3 Independent application for the physical-mathematical recitations

In order to further promote the interweaving of mathematics and physics, the physics exercise sheets contain tasks that students can solve most effectively by the help of the mathematics they just learned. The students are asked to work on these task during their self-study time to prepare for the weekly recitations. Under guidance of an experienced teaching person, the students have the opportunity to present and discuss their solutions with their fellow students. Thus, the second self-study phase per topic serves as further independent practice and transfer space.

3 Digital elements for the self-study phase

Interactive H5P videos and formative tests are the main elements for the first self-study phase. They are online available to the students via the learning and course management platform Moodle. In accordance with the flipped classroom method, the students are asked to work through these digital media prior to the MaMe seminars. Thus, they prepare for these face-to-face classroom seminars and the respective independent application to solve tasks for the physics recitations (see Figure 1). With the topic calculus of complex numbers and its application in the mechanics (EP1) and the electrodynamics (EP2) courses the design and the function of the main digital elements of our blended learning math course are illustrated.

3.1 Interactive H5P mathematics videos

Research on the learning effectiveness of explanatory videos often criticizes the lack of learner activation and a resulting "tend to turn off" without thinking through what has been presented (Richtberg and Girwidz, 2019). On the other hand, Chong et al. (2019) found that interactive explanatory math videos are one of the most valued components of a well-received flipped classroom. Therefore, we decided for interactive videos as the central elements for the self-study phases in our blended learning MaMe scenario.

Additionally, the quality criteria of good explanatory videos by Kulgemeyer (2020b,a) were considered. While planing and producing the interactive videos, we took care that they are well structured with the precise and minimal explanation just necessary to understand the math principles which are highly relevant for the physics course. The content of the videos always adapt to prior knowledge, to relevant examples, analogies or models, respectively.

The videos contain interactive learning tasks which engage the learners to actively use the new information (Kulgemeyer, 2020a,b; Kim et al., 2014). These interactive elements were added to the videos by using the H5P software tool (see H5P Group, 2024).

The topics of the interactive videos and their math content are carefully selected to meet the requirements of the physics teacher training courses. While strictly building upon the knowledge taught at basic math courses at extended secondary schools in Germany (Kultusministerkonferenz, 2012), we ensure that students with good math skills will be able to follow the presentations in the video. For example, common number sets from natural to real numbers, basic algebraic transformations, analysis of functions of a single variable including the rule of their integration and differentiation are well covered in math courses at school. Thus, the videos do not repeat these basic school math. However, they strictly build on this knowledge and apply it to motivate and introduce mathematical methods which are new to the students.

Table 3 presents the content of our mathematical methods for the mechanics course by listing the titles of the interactive videos. For example, the videos and corresponding face-to-face seminars cover methods how to integrate differential equations to solve the equation of motion (seminars 2 and 3) and how to calculate volume integrals to determine the centers of masses and moments of inertia of ridged bodies (seminars 5 and 6). The MaMe seminar 7 introduces the calculus of complex numbers to describe mechanical oscillations. MaMe seminar 8 extends the basic knowledge on algorithms to integrate the equation of motion from seminars no. 2 and 4 in order to find the general solution of the equation of motion for the damped oscillator. Here, the calculus of complex numbers just learned during seminar 7 is applied to derive the characteristic equation of the homogeneous linear differential equation of second order by using the ansatz of an exponential function.

In our scenario, we cover the required 10 math topics (see Table 2) during the mechanics course with two interactive videos per topic, see Table 3. The 18 videos for topic 2 to 10 have on average a duration of 12 min and 50 s excluding the time, the students require for working with the interactive elements. Generally, the first videos of each topic focuses on the introduction to the new mathematical methods. They are on average 1 min 10 s shorter than the second video applying the newly learned math to solve a physics problem or to derivate an important equation treated in the physics lecture. Each video contains two to three interactions. The first interaction starts in the first videos on average after 3 min and 35 s, in the second videos after about 6 min 45 s.

Various types of interactions are implemented. Generally, after key statements, accompanying complex mathematical derivations and algebraic transformations, respectively, the students are ask to answer single- or multiple choice questions and drag and drop tasks, to solve short math problems and to complete or to reproduce a mathematical derivation or algebraic transformation, respectively. These interactive task require the students to apply the math content just learned. Thus, the transfer of knowledge is initiated while the video is still being processed. Further interactive buttons, such as jumping in the video depending on the answers to the questions or buttons with hidden basic or further information offer a wide range of differentiation for the heterogeneous learning group of first-year students (Diekjürgen and Minah, 2021; Finkenberg, 2018; Volk, 2020). Students are free to decide when, where or how often they watch the videos.

Figure 2 presents three examples for such interactions incorporated via H5P in the two math videos for the topic 7 introduction to complex numbers and their application to describe oscillations. The first task (left part of Figure 2) ask the students to find the conjunct complex number z^* to a given complex number z and than to calculate the product zz^*. If the students get the correct result, which is nothing else than the square of the absolute value of z, they may choose "Go on" and the video continues or they click on the button (+) to receive a detailed explanation on how to calculate the requested product. The second task (right part of Figure 2) presents a drag and drop selection in which the students shall assign sine and cosine functions representing real harmonic mechanical oscillations to its complex notation using the complex exponential function.

Especially the interactive tasks challenge learners to think along and proverbially interact with the video. Individual feedback shows learners their level of learning and proposes a path how to continue the learning with the video. E.g., solving a task can always be repeated, alternative explanations in text form may be provided or a different mathematical presentation of the same content or law is presented. For each correctly solved task the students receive a certain number of points. These points are summed up and their total number is presented as individual feedback to the student at end of the video. Thus, these type of video interactions serve also as first formative tests. They provide the students an immediate feedback to their short-term learning success.

3.2 Formative tests

Still during the first self-study phase for each topic but after watching and working through the corresponding two interactive videos the students may perform additional formative tests. In order to motivate the students to work on the tasks, we have designed varied gamified and interactive environments using the H5P modules Interactive Presentations and Game Map (Manzano-León et al., 2021; Ariffin et al., 2022). The tasks are always based on the main content of the videos. The tests require students to apply the mathematics just learned in simple examples and are intended to prepare them for tasks during the upcoming face-to-face seminars (Kim et al., 2014).

Figure 3 presents an example game map referring to the scenario of complex numbers (topic 7 in Table 2). On the left side, tasks are hidden behind the six named yellow places at a fictive map. A selection of possible path ways is illustrated. The students may determine their own learning path by working on the tasks hidden behind the named places. They do not have to scroll through all places and solve all tasks. If a question has been solved correctly, the place turns green (see left part of Figure 3). The different tasks are mostly multiple or single choice questions, drag and drop tasks or text fields as e.g shown on the right part of Figure 3. Graded help is provided for difficult tasks to offer a wide range of differentiation (Diekjürgen and Minah, 2021; Finkenberg, 2018; Volk, 2020). In such case, there are interactive presentations hidden behind the yellow places, containing the task and graded help as following linked slides.

For all the formative tests during the self-study phases, the students receive automated personalized feedback on their

TABLE 3 Subjects of the two MaMe videos to prepare for each of the 10 face-to-face MaMe seminars and the sample application of the new math discussed during respective seminar.

No.	Topics of the mechanics lecture	First video: introduction to mathematics	Second video: application of mathematics in physics	Application of the video content during the face-to-face seminar
List of the MaMe videos and seminars associated to the lecture topics for the mechanics course				
1	Introduction	Introduction to the mathematical methods	Digital measurements and data analysis in physics	Introduction to the apps "phyphox" and "Origin"
2	Mechanics of a point mass	Functions and vectors to describe physical laws	Derivation and analysis of the trajectory of a projectile motion	Derivation and analysis of the path curve of a cycloid
3	Newton's axioms and conservation of energy	Introduction to differential equations and separation of variable	Derivation of the second cosmic velocity by integration of the equation of motion for the gravitational force	Analysis of trajectory and velocity of the motion of a body on a spring (phase space representation)
4	Equation of motion of a particle in non-constant force fields	Integration by parts and substitution	Derivation of the velocity function for free fall in an uniform gravitational field with air resistance	Velocity dependent friction forces—solving the equation for a rising bubble in water
5	System of point mass and conservation of momentum	Volume and mass integrals	Calculation of the center of mass	Calculation of volumes and centers of masses for a droplet-like body of revolution and an inhomogeneous cube
6	Rotational motion of a rigid body	Mass and volume integrals to deviate the moment of inertia for ridged bodies	Moment of inertia of ridged bodies of revolution and the parallel axis theorem	Derivation of the moment of inertia homogeneous cuboid to prepare for the home lab experiment "The overturning smartphone"
7	Mechanical oscillations	Introduction to complex numbers: arithmetic and graphical representations, calculus, complex conjugate	Complex functions to describe and superimpose two harmonic oscillations	Graphical and arithmetical addition of two oscillations with equal angular velocity
8	Free, damped and forced oscillator	Classification of differential equations and exponential ansatz to solve a linear, homogeneous differential equation	The mathematical description of an free damped oscillator	The damped motion of a shock adsorber
9	Mechanics of deformable solids and fluids	Power series expansions and approximation polynomials of functions—Insightful examples	Expansion of the sine and ln functions in Taylor and Mac-Laurent series	Exponential functions, their series expansions and approximation polynomials
10	Gravity as a conservative force field	Introduction to vector analysis: The differential operators grad and curl	The curl and gradient of the gravitational force	Transformation between force and energy for a rod compression following Hooke's law

individual learning status. If the students decide to submit their results back to the course management platform, the teaching stuff receives anonymous information about the level of knowledge from the entire group. Submitting the results by the students is deliberately voluntary in order to separate the learning area of the self-study phase from the performance areas (Helmke and Schrader, 2009).

4 Methods

4.1 Implementation

The integrated cross modular mathematics education for the physics teacher trainees as introduced in Table 2 was first tested during the winter term 2022/23 and the subsequent summer term 2023 (see Figure 4). Based on the experiences of the teaching stuff and the feedback from the students, the interactive math videos and

the formative testes for the self-study phase were completed and improved. During winter term 2023/24 the math education within the mechanics module (EP 1) implemented all the topics with the corresponding interactive videos given in Table 3.

4.2 Investigation on the quality of the material and the learning effectiveness

The acceptance of the digitally available materials and the new course design by the students was surveyed via questionnaires. The accompanying study was conducted for the two lessons on complex numbers in mechanics on describing mechanical oscillations (T1) and in electrodynamics on deriving and working with impedance (T2; see Figure 4). The first test (T1) examines students opinions on the quality of the interactive videos and on the three pillars of the course design: interactivity, parallelism to the physics lecture
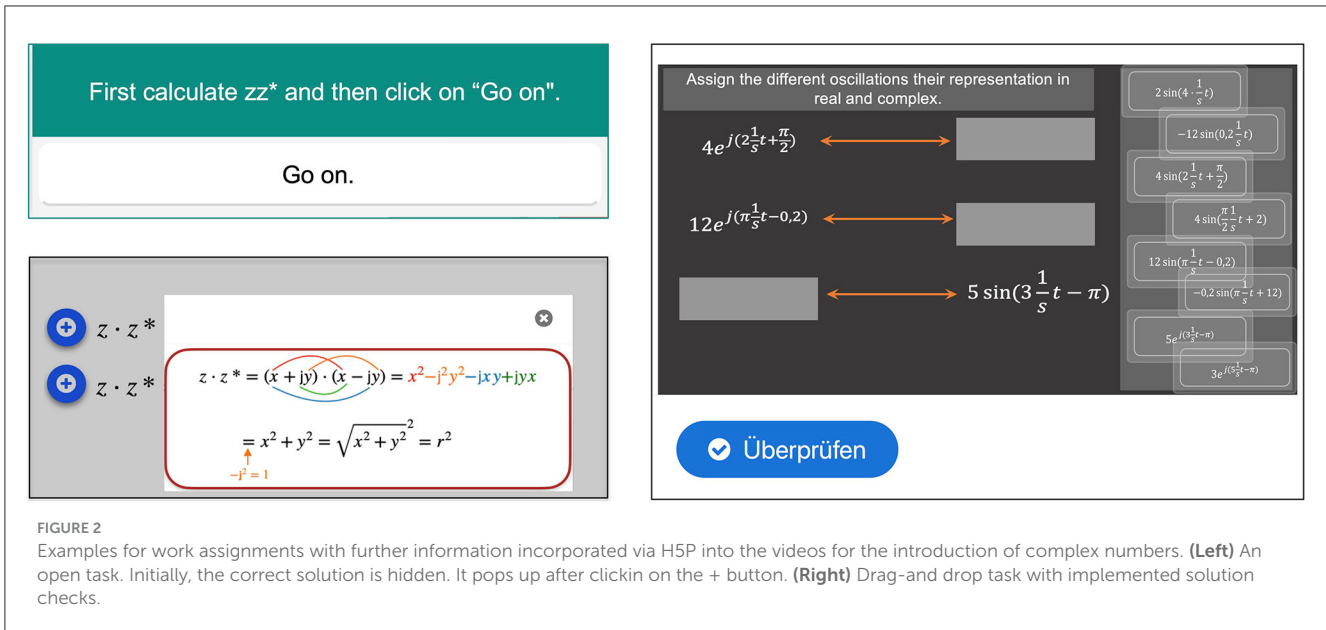
First calculate zz* and then click on "Go on".

Go on.

$z \cdot z *$

$z \cdot z *$

$z \cdot z * = (x + jy) \cdot (x - jy) = x^2 - j^2 y^2 - jxy + jyx$

$= x^2 + y^2 = \sqrt{x^2 + y^2}^2 = r^2$

$-j^2 = 1$

Assign the different oscillations their representation in real and complex.

$4e^{j(2\frac{1}{s}t + \frac{\pi}{2})}$

$12e^{j(\pi\frac{1}{s}t - 0,2)}$

$5\sin(3\frac{1}{s}t - \pi)$

$2\sin(4 \cdot \frac{1}{s}t)$

$-12\sin(0,2\frac{1}{s}t)$

$4\sin(2\frac{1}{s}t + \frac{\pi}{2})$

$4\sin(\frac{\pi}{2}\frac{1}{s}t + 2)$

$12\sin(\pi\frac{1}{s}t - 0,2)$

$-0,2\sin(\pi\frac{1}{s}t + 12)$

$5e^{j(3\frac{1}{s}t - \pi)}$

$3e^{j(3\frac{1}{s}t - \pi)}$

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FIGURE 2
Examples for work assignments with further information incorporated via H5P into the videos for the introduction of complex numbers. **(Left)** An open task. Initially, the correct solution is hidden. It pops up after clickin on the + button. **(Right)** Drag-and drop task with implemented solution checks.
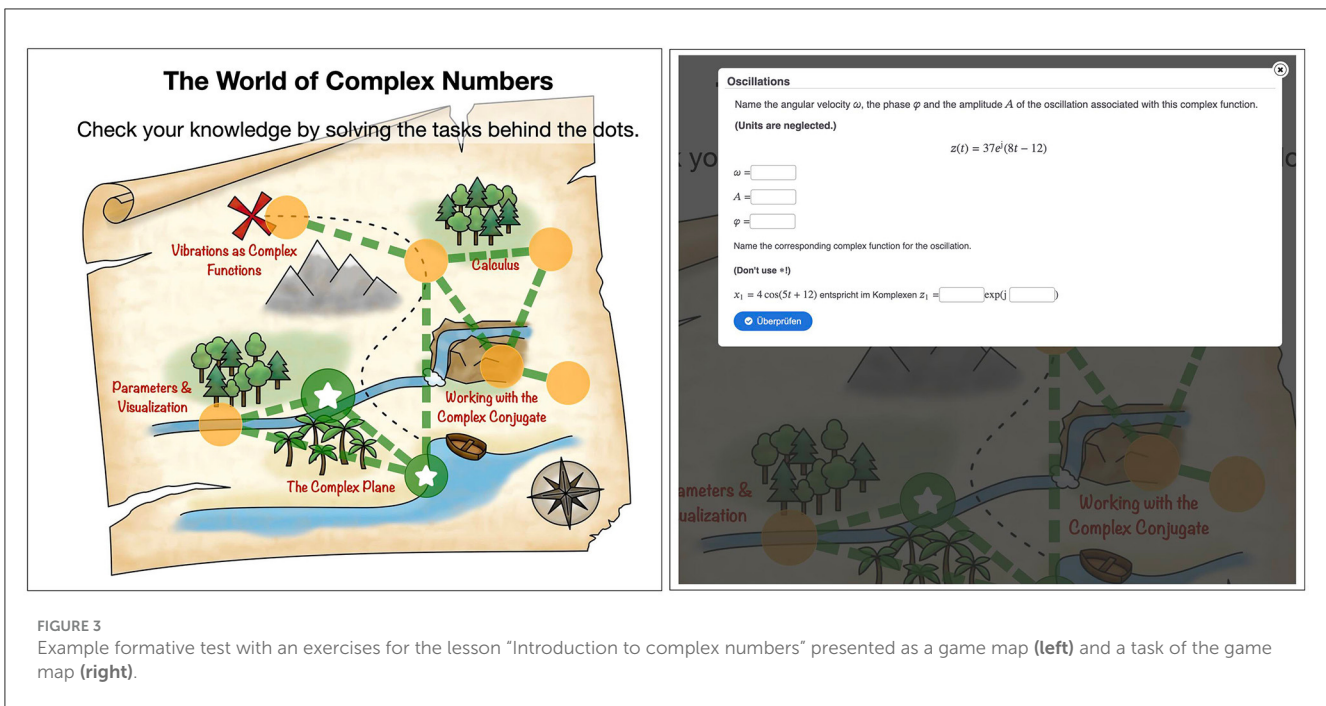
The World of Complex Numbers

Check your knowledge by solving the tasks behind the dots.

Vibrations as Complex Functions

Calculus

Parameters & Visualization

Working with the Complex Conjugate

The Complex Plane

Oscillations

Name the angular velocity ω, the phase φ and the amplitude A of the oscillation associated with this complex function.

(Units are neglected.)

$z(t) = 37e^{j}(8t - 12)$

$\omega =$

$A =$

$\varphi =$

Name the corresponding complex function for the oscillation.

(Don't use *!)

$x_1 = 4\cos(5t + 12)$ entspricht im Komplexen $z_1 =$ ☐ $\exp(j$ ☐ $)$

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ameters & ualization

Working with the Complex Conjugate

FIGURE 3
Example formative test with an exercises for the lesson "Introduction to complex numbers" presented as a game map **(left)** and a task of the game map **(right)**.

and spiral-curricularity. The second test (T2) took place at the end of the second semester. Here, the students were asked about the quality and acceptance of the overall design of our cross-modular math course.

These two quality surveys are each linked to knowledge tests in which students are tested on their newly acquired (K1) or memorized (K2) knowledge of complex numbers (see Figure 4). A third test (K3) took place during the general physics laboratory in the semester break after the electrodynamics (EP2) course (see Figure 4). It detected the long-term knowledge of the application of complex numbers to describe ac-circuits.

4.2.1 Survey on the quality of videos (T1)

As the acceptance of the new materials and teaching formats is necessary for the successful implementation of the course, the first survey focused on the acceptance and quality of the interactive explanatory videos. The survey examines the research questions:

Q1 Do the interactive elements encourage students to actively work on the videos? (interactivity)

Q2 Do the students recognize the relevance of mathematics for describing current phenomena in the physics lecture? (parallelism to physics lecture)
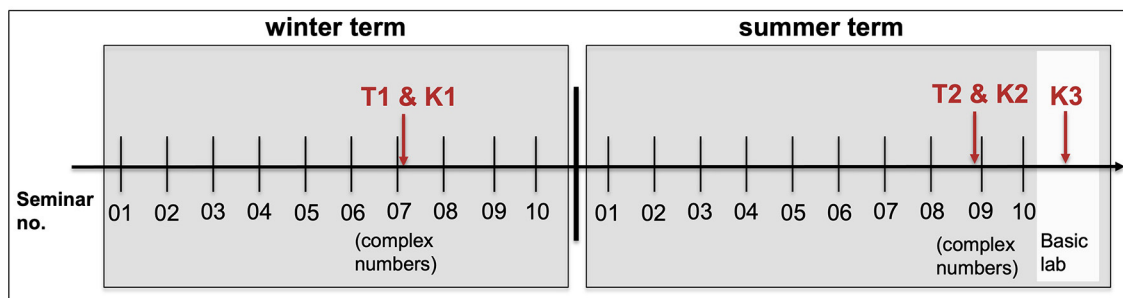
FIGURE 4
Time schedule of the MaMe seminars during the two successive semesters. The numbers refer to the topics given in Table 2. The arrows indicate surveys and tests on the quality of the materials (T1 and T2) and the learning effectiveness (K1, K2, and K3).

Q3 Do the videos build on existing prior knowledge in a spiral-curriculum? (spiral-curricularity)

Q4 Do students generally rate the videos as good explanatory videos?

For each of the first three research questions Q1–Q3 a single item was formulated. These items were adjusted to fit the topic of complex numbers to avoid misunderstandings. E.g., the item for question Q3 (spiral-curricularity) ask for the level of the students agreement to the statement weather they understood the analogies between complex numbers and the prior knowledge on vectors.

To examine the research questions Q4, we obeyed Kulgemeyer's list of criteria for good explanatory videos (Kulgemeyer, 2020b,a). This part of the questionnaire T1 consists of 15 items, which investigate the seven factors of good science explanation videos: structure, adaption, tools for adaption, minimal explanation, highlighting relevance, follow-up learning tasks, new/complex principles (Kulgemeyer, 2020a,b).

The survey on the quality of the explanatory videos was conducted with two successive cohorts of physics teacher trainees in winter term 2022/23 (cohort C1) and 2023/24 (C2). The number of participating students was 41 and 21, respectively. The students were asked to rate their agreement to the 15 items using a four-point Likert scale. We use diverging stacked bar charts to illustrate the assessments of the quality features of the videos (Robbins and Heiberger, 2011). The proportion of the participants who rather disagree or disagree at all with a statement are plotted on the left side of each graph and the proportion of participants who rather agree or agree at all are shown on the ride side. These four answer options of the Likert scale are color-coded and equated to a value (disagree at all $\hat{=}1$, rather disagree $\hat{=}2$, rather agree $\hat{=}3$, agree at all $\hat{=}4$). This allows us to calculate a mean agreement value μ and a standard deviation σ for each item (Veith et al., 2022).

4.2.2 Survey on the quality of the entire course design (T2)

The second survey (T2) was conducted at the end of the second semester. By this time, the students are familiar to the new blended learning concept of the mathematical methods education and, thus, able to evaluated the quality of the whole course design from their own prospect. Based on the model of good university

teaching (Ulrich, 2016; Biggs, 2003; Ledić et al., 1999) and the 10 criteria of good teaching (Meyer, 2003; Helmke and Schrader, 2009), a questionnaire was developed. The survey focused on the dimensions of the teaching and learning process via the two research question:

Q5 Do the students rate the teaching of the MaMe course as good teaching?

Q6 Do the students rate their learning process positively?

The teaching quality (Q5) is characterized by the two items structure and transparency and feedback and individual support. These items are described in detail by Helmke and Schrader (2009) and Meyer (2003). Based on these description, we developed five questions on the item structure and transparency and two questions on the item feedback and individual support. In the same way, we formulated a questionnaire to evaluate the learning process (Q6) with two questions on the students' motivation and four questions on the intensive use of learning time.

Also this survey (T2) applied a four-point Likert scale to examine the students opinion on the quality of the course design. It was conducted at the end of the summer term 2023 (see Figure 4) with 16 participants of the cohort C1. The results were analyzed in the same way as described for survey T1.

4.2.3 Surveys on the learning effectiveness of the MaMe course (K1, K2 and K3)

In order to describe the model of good university teaching through the effect of specialist knowledge and competence, the applicability of the knowledge was determined in two tests on calculus of complex numbers, the knowledge tests (K1 and K2, see: Figure 4). The first test K1 was conducted directly after the two interactive videos, which introduced complex numbers to describe oscillations (see Table 3). The second test K2 took place just before the complex numbers were treated again to describe complex resistors. K2 measures the retrievability of the knowledge on the calculus in complex numbers. Both tests K1 and K2 consisted of similar tasks and covered key aspects of complex numbers, such as the complex plane and the description of harmonic oscillations as complex function. The tests included 11 short tasks focusing on the

arithmetic operation with complex numbers. The tests K1 and K2 compare the short term and the long term knowledge. To illustrate the differences between both test results the total test scores are compared by means of a Mann–Whitney U-test, for details see Nachar (2008).

Additionally, the competence of application of complex numbers were measured with a third test K3 which took place at the end of the electrodynamics course (EP 2) during the physics laboratory (see Figure 4). The participants of the lab course were our physics teacher trainees and students enrolled in the bachelor of science physics study program. While the physics education is similar in both programs, the math education for the B. Sc. physics students takes place in a conventionally setup with face-to-face lectures and recitations every week. Thus, we compared the applicable knowledge on the calculus of complex numbers of these two groups just prior to an lab experiment, in which the students were prepared to measure voltages and currents on complex resistors and phase shifts in RCL series circuits. During the test K3 both groups of students were ask solve task to complex resistors, their position in the complex plane and the derivation of the impedance and phase shift for an RCL series circuit. The results of the test K3 were compared using the a Mann–Whitney U-test. The effect size of the intervention is described in more detail using the biserial rank correlation r to assess the magnitude of statistically significant effects.

5 Results and discussion

5.1 Survey on the quality of videos (T1)

5.1.1 Q1: Do the interactive elements encourage students to actively work on the videos?

Figure 5 shows the opinion of the students on the interactivity of the videos in winter term 2022/23 and 2023/24. 78.1 and 90.5% of the participating students stated that the interactive elements of the video encouraged them to actively work on the content. In an optional free text field, 27 of the total 62 respondents of the two cohorts C1 and C2 explicitly praised the interactions as motivating and promoting for the understanding of the mathematical content. Some students even asked for more interactive elements. These results shows that the interactive elements encourage students to work actively on the videos.

5.1.2 Q2: Do the students recognize the relevance of mathematics for describing current phenomena in the physics lecture?

The parallel development of the mathematics to the physics lecture intended to strengthens the relevance and connectivity of the mathematical methods and the physics lecture. Figure 5 shows, that 90.2% of the students of cohort C1 and 81.0% of the students of cohort C2 recognize the relevance of the mathematical methods for the parallel physics lecture. The high mean agreement values ($\mu = 3.10$ and $\mu = 3.32$) illustrate the high relevance of the mathematical content for the physics in the students point of view. Thus, the interlocking of physics and math education in one

module and the blended learning concept for the math education may be considered as very obvious to the students.

5.1.3 Q3: Do the videos build on existing prior knowledge in a spiral-curriculum?
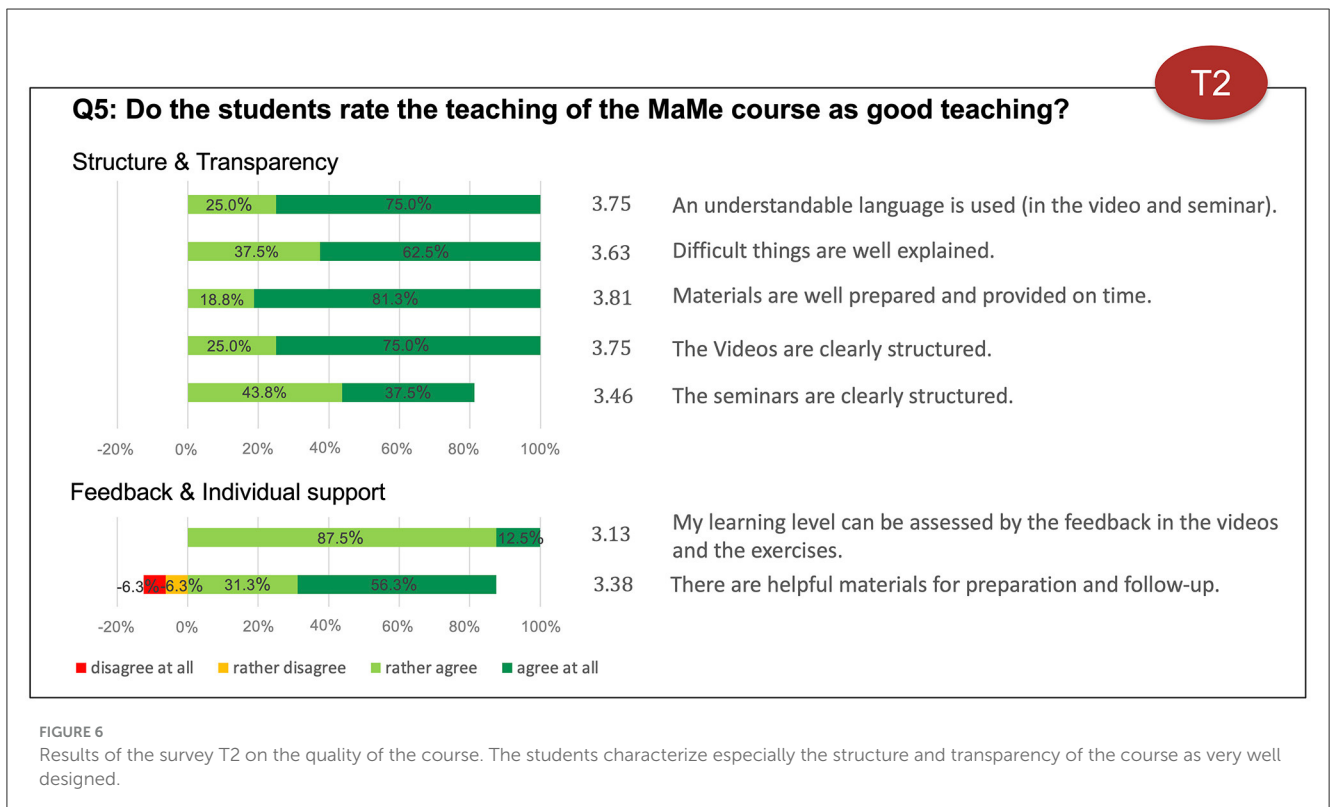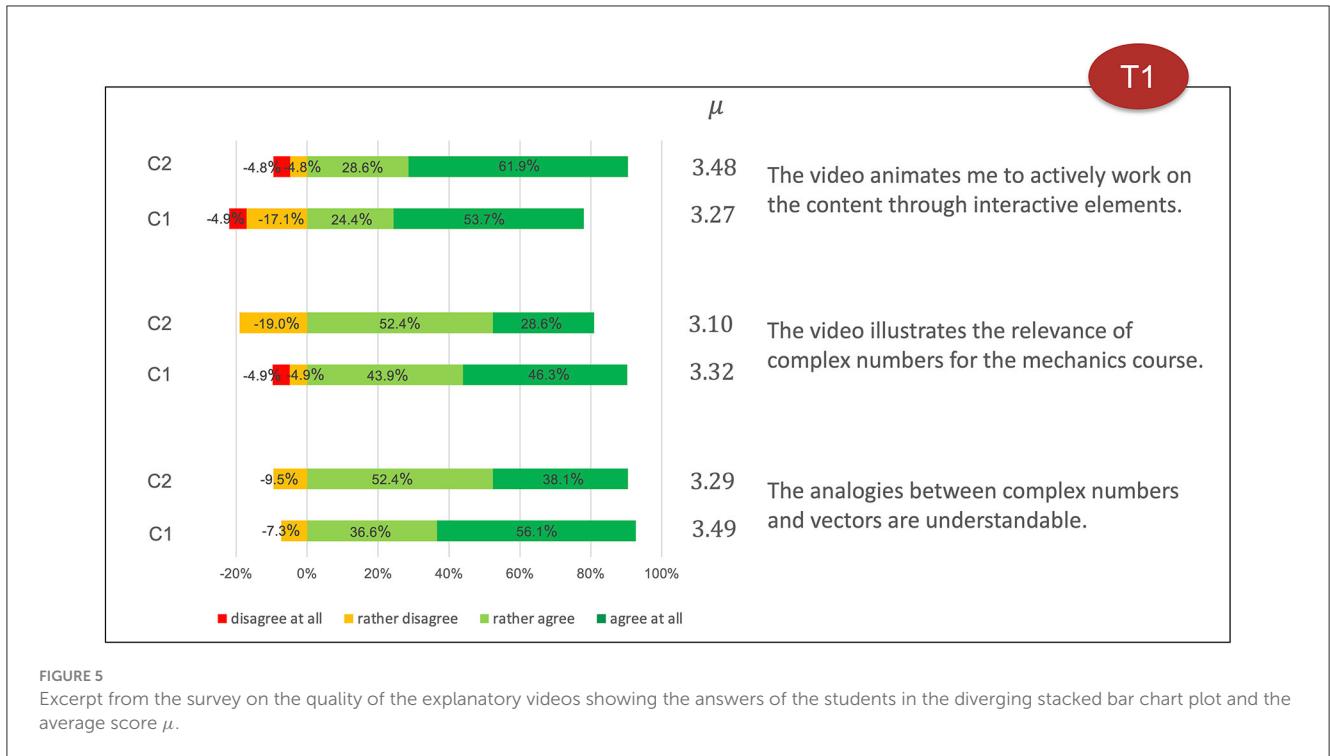
The spiral-curricular approach throughout the whole course is one of the main characteristics of our new blended learning math course. Figure 5 shows, that 92.7 and 90.5% of the respondents in the two cohorts, respectively, rated the analogy of complex numbers to vector calculus in two dimensions as prior knowledge from upper secondary school as understandable. The high mean agreement scores of $\mu = 3.49$ and $\mu = 3.29$ show that our MaMe course design with the interactive videos as their central element fulfilled our intentions with respect to the spiral-curricular extension of the math competences of the students. That the knowledge has been expanded is evident from the knowledge tests K1-K3.

5.1.4 Q4: Do students generally rate the videos as good explanatory videos?

The evaluation of the three video characteristics interactivity, adaption to prior knowledge and highlighting relevance is also shown in Figure 5. From the students' prospect, these features were implemented well to very well in the explanatory videos (predominately scores 3 and 4 on the Likert scale). An analysis of all 15 items of good explanatory videos also yields ratings between $\mu = 2.78$ and $\mu = 3.6$. The average rating of all factors is $\mu = 3.29$ ($\sigma = 0.22$). The standard deviation for the mean score is low which means that the students responses were relatively stable across all participants and even across the two successive cohorts of first year physics teacher trainees. Similar good and stable results are also measured for the seven factors of good explanatory videos. From the factor tools for adaptation (Kulgemeyer, 2020a), our students rate the features analogies ($\mu = 3.41$), level of mathematization ($\mu = 3.45$) and representation forms ($\mu = 3.56$) for example as very good. These results demonstrate the high quality and at the same time the high acceptance of the explanatory videos as the element of the blended learning MaMe education. Generally, we may conclude that the students evaluate the videos as good explanatory videos.

5.2 Study on the quality of the entire course design (T2)

The quality of the whole course could so far only be evaluated by the cohort C1 starting in winter term 2022/23. Since the survey T2 took place during the second semester the number of participants in this survey dropped down to $N = 16$. The main value for the rating of all items evaluating the teaching quality and the learning process is $\mu = 3.49$ ($\sigma = 0.24$). It shows that the students were very satisfied with our course design and with the presentation of its components (compare Sections 5.2.1, 5.2.2).

FIGURE 5
Excerpt from the survey on the quality of the explanatory videos showing the answers of the students in the diverging stacked bar chart plot and the average score μ.

FIGURE 6
Results of the survey T2 on the quality of the course. The students characterize especially the structure and transparency of the course as very well designed.

5.2.1 Quality of teaching

The quality of teaching has two dimensions, structure and transparency and feedback and individual support. Figure 6 shows that the students rated all seven items of the survey according to Q5 predominately positive with scores of $\mu > 3$. The key aspects

of quality of structure and transparency, comprehensible language ($\mu = 3.75$, $\sigma = 0.11$) and the ability to explain difficult issues simply ($\mu = 3.63$, $\sigma = 0.23$) were evaluated by the students as very good. The materials and videos were well prepared and provided in time ($\mu = 3.81$).

The second part of the survey is *feedback and individual support* (see Figure 6 last two items). The first of these two items shows that all students recognize the feedback from the interactive videos and from the exercises as good or even very good. They rated this feedback system with the main value of $\mu = 3.13$, ($\sigma = 0.11$) as good. The majority of students are satisfied with the materials offered for preparation and follow-up ($\mu = 3.38$, $\sigma = 0.73$). In an optional text field, some student even suggested to provide additional materials. Thus, our blended learning MaMe seminar represents a teaching-learning scenario which fulfills the quality criteria of good teaching.

5.2.2 Quality of the learning process

Figure 7 displays the results of the survey T2, research question Q6, investigating the quality of the learning process. It represents a measure for the students ability to learn intensively by using the supplied digital materials and the support by the teachers. The mean value for all items referring to the intense use of learning time is $\mu = 3.43$ ($\sigma = 0.27$). Important content was consolidated through repetition and discussion during the seminar ($\mu = 3.44$, $\sigma = 0.25$). The suitability of additionally offered material and its contribution to the students' level of learning were rated well ($\mu \geq 3.00$, $\sigma = 0.38$), but could obviously still be improved. All of the students also positively recognized the relevance of mathematical methods for physics ($\mu = 3.63$) and all respondents stated that they would continue to use the materials, in particular the seminar scripts during their studies. In summary, the 16 participating students of cohort C1 were very motivated to use our teaching-learning offers (see Figure 7).

5.3 Learning effect

The knowledge and competences of the students in the field of complex numbers and its application to physics problems was measured by three successive knowledge tests K1, K2 and K3. In this section, only the results of the cohort C1 starting in winter term 2022/23 are discussed, since the cohort C2 had not yet finished its second semester at the time of submission of this manuscript.

5.3.1 Short-term (K1) and long-term (K2) applicability of complex numbers

Figure 8 compares the results of the two tests K1 and K2 assessing the mathematical knowledge memorized immediately after the introduction of complex numbers and still available after 6 months. The rose bars (K1) represents the knowledge on the calculus of complex numbers immediately after its introduction during session 7. On average, the students achieved 7.7 ($\sigma = 2.54$) out of 11 points. The results of the very similar test K2 are presented by the blue bars. During this second test the participants achieved an slightly better average score of 8.5 points ($\sigma = 2.46$) out of 11 points. In all except two tasks, the students gained better results than in the first test. The majority of students improved their knowledge on the different forms of complex numbers and were able to work with their representation. Also the description of oscillations as complex functions stayed well memorized, even over

6 months. The last three bars in Figure 8 show an improvement in the work with the complex conjugate. The change in the total number of points achieved in the tests after a few days and 6 months was examined using a Mann–Whitney U-test. The test indicated that the difference of scored points is not statistically significant [$U(N_{\text{short}} = 24, N_{\text{long}} = 10) = 100$, $p = 0.46$]. This result shows that the knowledge regarding the calculus of complex numbers was transferred to long-term memory.
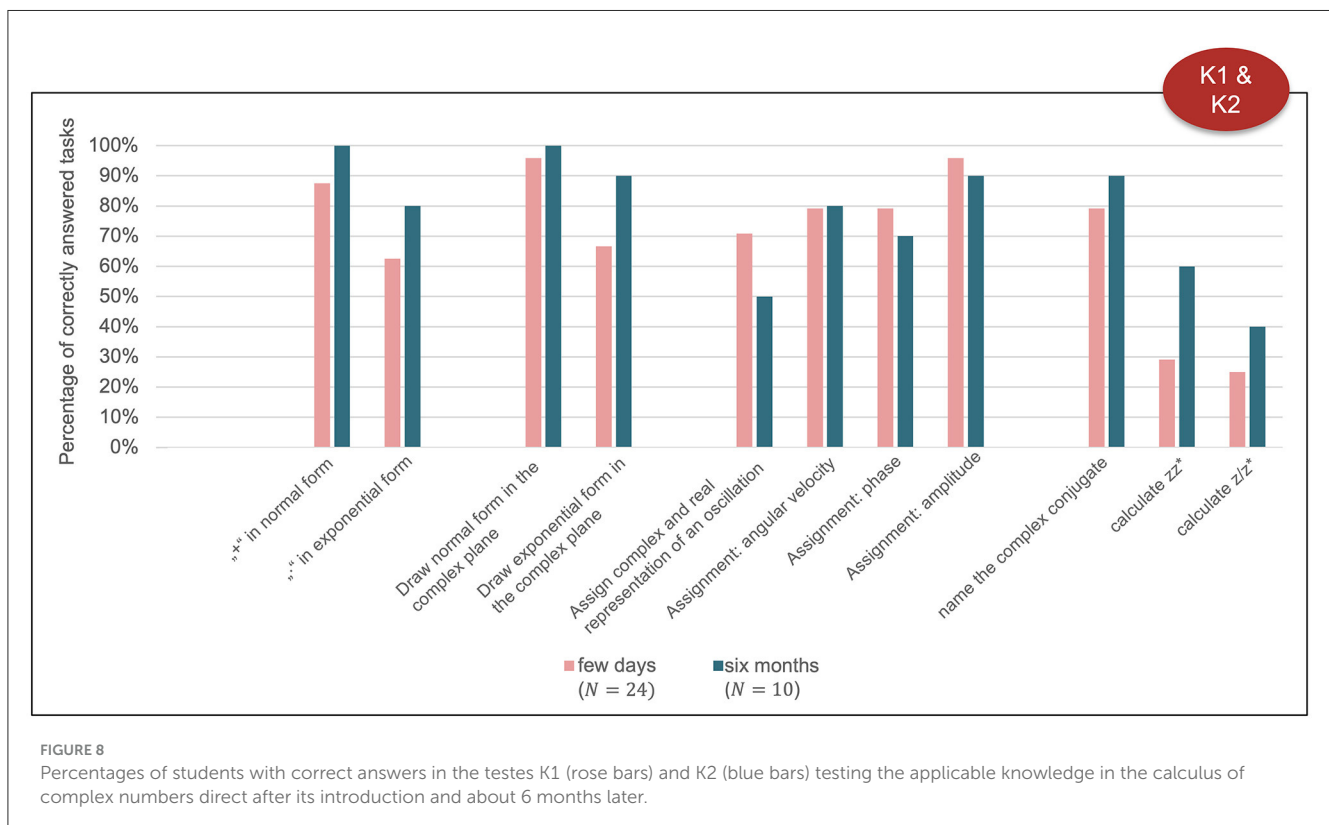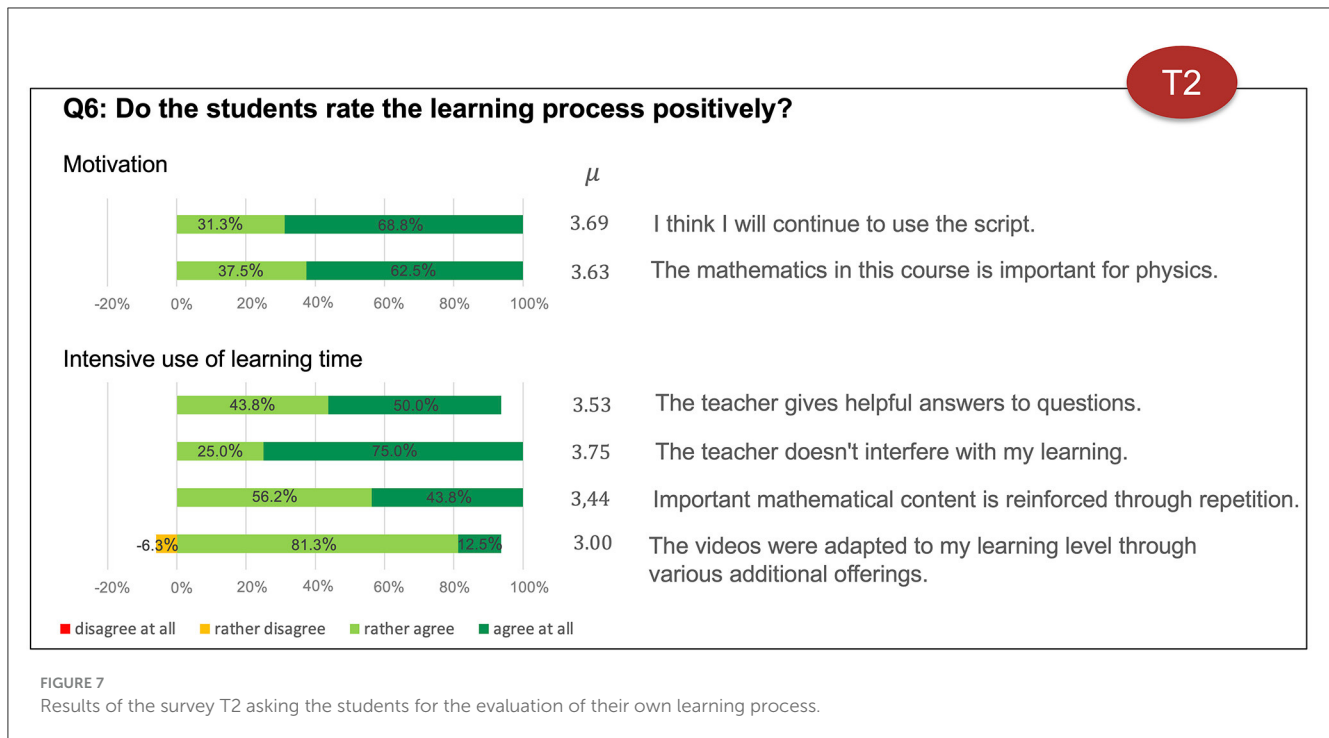
5.3.2 Comparative study on long term knowledge and applicability of complex numbers (K3)

Figure 9 shows the results of the test K3 comparing the knowledge of two different courses on the subject of complex numbers. The blue bars represent the results of the cohort C1 of physics teacher trainees, which experienced the math education via our blended learning math course. The red bars are the results achieved by students of the bachelor of science physics course who received a separate math education via conventional weekly face-to-face lectures and recitations. With the exception of the last question (impedance of RCL circuits), both groups of students achieved satisfactory to good results. The last two questions deal with the calculation of the impedance of the RCL-circuit and the resulting phase shift of the impedance using the representation of impedances in ac circuits by complex numbers. Especially the last two bars (impedance of RCL circuits) display noticeable differences in the percentage of correct answers. 89.3% of the teacher trainees and only 52.4% of the bachelor of science physics students were able to calculate the phase shift of the impedance.

The physics teacher training students achieve an average of 7.50 ($\sigma = 1.4$) points and bachelor's students 5.98 ($\sigma = 2.36$) out of eight points. The Mann–Whitney U-test indicates that the difference is statistically significant, with the data $U(N_{\text{teacher}} = 28, N_{\text{bachelor}} = 42) = 327$, $p < 0.001$, $r = 0.445$. The effect size of the MaMe seminar is estimated using the biserial rank correlation r with a value of $r = 0.445$ as a medium effect, close to a high effect size ($r \geq 0.5$) according to Cohen (2013). Thus, for the topic of complex number and its application to the physics of ac circuits an intermediate to strong effect on the learning effectiveness in favor of our blended-learning math approach is observed if compared to students who received their math education in a standard separate face-to-face lecture and recitation setting.

6 Summary

Blended learning approaches have become an important area of research and development in recent years. The approach presented in this paper represents a flipped classroom approach to mathematics education for physics teacher trainees. It covers all the necessary mathematics during the first two semesters of the physics education. We integrated the mathematics into the first two physics courses and developed a comprehensive list of topics that represent the minimum knowledge and competencies that physics teacher candidates need at the beginning of their studies. Design principles and best-practice examples were used to build the course. Interactive videos are the key element of the self-study. They have been produced according to the criteria of good explanatory videos.

Q6: Do the students rate the learning process positively?

FIGURE 7
Results of the survey T2 asking the students for the evaluation of their own learning process.

FIGURE 8
Percentages of students with correct answers in the testes K1 (rose bars) and K2 (blue bars) testing the applicable knowledge in the calculus of complex numbers direct after its introduction and about 6 months later.

The accompanying research focused on the quality and learning effectiveness of the course. The main results are:

- The orientation of the course on the quality criteria of good university teaching and the common design principles of a

flipped classroom as well as the interactive videos as main digital element of the course (Ulrich, 2016; Helmke and Schrader, 2009; Biggs, 2003; Ledić et al., 1999; Kulgemeyer, 2020a,b; Kim et al., 2014) achieve a high level of student acceptance.
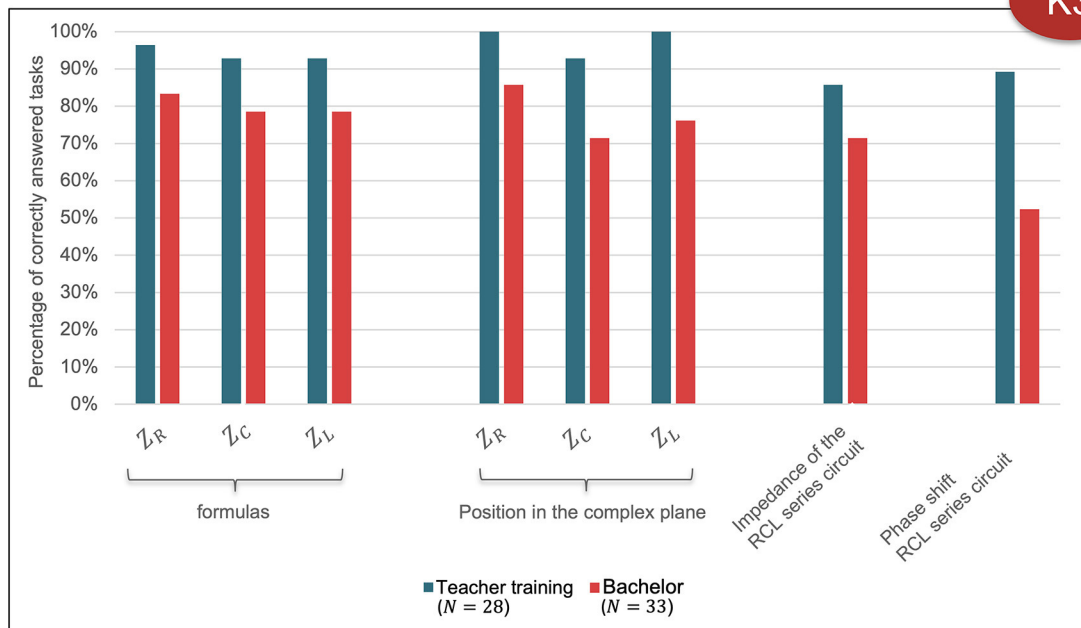
FIGURE 9
Results of the comparative test K3 on the calculus of complex numbers between the physics teacher training students (blended learning MaMe education) and the physics bachelor students (traditional weekly face-to-face lectures and recitations). Both groups of students achieve mostly good to satisfactory scores.

- Interactive elements in videos motivate learners to actively work with the videos. In agreement with results published by Chong et al. (2019), Kraemer and Liebendoerfer (2022), and Priyakanth et al. (2021), our students report that the interactive elements enhance their understanding.
- Self-regulation is key to the success of a blended learning format (Finkenberg, 2018). Interactive elements of the videos and assignments with immediate feedback help students assess and individualize their learning path (Chong et al., 2019; Kim et al., 2014). This means that one of the success factors of the blended learning math course is to support the students by appropriate, didactically prepared materials (Pilotto, 2021; Fischer, 2014).
- In agreement with numerous studies that show comparable or better results from a blended learning approach than from face-to-face teaching (Quinn and Aarão, 2020; Chong et al., 2019) our blended learning math approach for the physics teacher trainees achieved a significantly better outcomes in the field of complex numbers compared to a standard face-to-face weekly lecture and recitation setting of a similar study program for bachelor of science physics students.

7 Outlook

During the summer term 2024 we are going to complete the interactive videos and further digital elements of our spiral-curricular blended learning math education accompanying the physics course in electrodynamics during the second semester.

We will also include important math topics such as solving differential equations and the introduction to vector analysis into the surveys in order to provide further evidences of the course's effectiveness. In order to gain a deeper understanding of the factors that promote and inhibit the concept, interviews and open surveys on the course will be conducted in a subsequent study.

Data availability statement

The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

Author contributions

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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