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Physics teacher training students' understanding of Gauss's law of electricity by a blended learning course

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Abstract

The implementation and evaluation of an interactive blended learning scenario on Gauss's law of electricity for the experimental physics course on electrodynamics for physics teacher trainees is presented. The course meets the needs of teacher trainees' tightly timed study program by providing the necessary mathematical knowledge via seminars that run alongside the physics lectures. During the intervention, students become increasingly confident in their calculation skills required to apply Gauss's law of electricity. A post-intervention concept test shows that students have a good knowledge of working with closed surfaces when applying Gauss's law of electricity. However, conceptual difficulties regarding the recognition of symmetries of charge distribution and the tendency to incorrectly transfer the model of conductive hollow bodies to insulators prove difficult to overcome for the students. Therefore, we recommend clearly distinguishing between the properties of conductors and insulators when an external electrical field is applied. The direct comparisons of their properties can be facilitated, e.g., by conducting experiments observing the shielding of the electric field by various conducting and insulating materials.

Keywords: Gauss's divergence theorem, Gauss's law of electricity, blended learning, mathematical methods

INTRODUCTION

The concepts of electrostatics and electrodynamics are difficult to grasp for science and engineering students due to their abstract mathematical description and the partial lack of visualization of microscopic effects. Many research projects therefore focus on students' understanding of electrodynamic concepts such as electric circuits (Engelhardt & Beichner, 2004; McDermott & Shaffer, 1992), superposition of electric fields (Campos et al., 2021, 2025; Hernandez et al., 2023, 2025; Rainson et al., 1994) and Gauss's law of electricity (Borges et al., 2024; Campos et al., 2021, 2023; Guisasola et al., 2008; Hahn & Klein, 2023, 2025; Hernandez et al., 2023, 2025; Isvan & Singh, 2007; Li & Singh, 2017; Li et al., 2023; Pepper et al., 2010; Singh, 2006). Various didactic approaches were developed and evaluated to address the difficulties associated with the understanding of Gauss's law of electricity. These approaches comprise a broad spectrum ranging from small-step, application-oriented tutorials (Isvan & Singh, 2007; Li & Singh, 2017; Li et al., 2023) or vivid VR environments (Borges et al., 2024) to abstract learning tasks focusing on the general handling and interpretation of vector analysis operators and Gauss's divergence theorem (Hahn & Klein, 2022, 2023, 2025).

None of the studies examined cohorts of physics teacher training students. The investigation of their conceptions is particularly interesting because the teacher training programs (as well as other programs with physics as minor subjects) usually have a different structure and shorter timetables for physics and mathematics courses than the pure physics study programs. This limitation opens a need for research to enable optimal learning conditions also for physics teacher training study programs in order to effectively overcome the striking hurdles of mathematics for students in the introductory study phase (Bauer et al., 2025; Kabashi et al., 2022; Kämpf and Stallmach, 2024b; Lumpe, 2019; Schild, 2021; Woitzik et al., 2023). The German teacher training program in physics (Woitzik et al., 2023) is unique, as it is founded on three equally

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Contribution to the literature

- To our knowledge, this is the first study investigating the conceptual difficulties experienced by physics teacher training students in the field of Gauss's law of electricity.
- This study also investigates the development of the self-concept of physics teacher training students with respect to the mathematics required for understanding of Gauss's law of electricity taught via a blended learning mathematical methods seminar integrated into an electrodynamics physics course.

important pillars: the two teacher training subjects and educational sciences. Since less than half of physics teacher training students study mathematics as a second subject (Woitzik et al., 2023), all the necessary mathematical concepts for successfully studying physics must be covered during the study time allocated for the physics education of the teacher training students. For the physics teacher training study program at Leipzig University, we have designed and evaluated an approach integrating mathematics into experimental physics modules sustainably (Kämpf and Stallmach, 2023, 2024a, 2024b; Kämpf et al. 2025a). The central concept is to incorporate mathematical methods into interactive, spiral-curricular, blended learning seminars, running alongside the current experimental physics courses on mechanics (first semester) and electrodynamics (second semester), to make the mathematics applicable by concrete links to physics.

This paper examines the evolution of students' confidence in calculator competencies used for Gauss's law and the conceptual understanding of Gauss's law of electricity after our intervention. The students' confidence development during the intervention was examined using three self-assessments, at the beginning, in the middle and at the end of the intervention. To assess students' conceptual knowledge, an extract from Singh's (2006) concept test was carried out at the end of the intervention. The results are compared with those of similar studies, and implications for revising the course are derived.

THEORETICAL BACKGROUND

Gauss's Divergence Theorem: A Brief Overview

Gauss's divergence theorem is given in Eq. (1):

$$\phi = \oiint \vec{F} \cdot d\vec{A} = \iiint (\vec{\nabla} \cdot \vec{F})\, dV, \tag{1}$$

which equates two expressions for calculating the flux ϕ of a vector field $\vec{F}$ through a closed surface A. The two terms represent the surface integral of the vector field and the volume integral of the flux density ϱ_F of the vector field, which correspond to the divergence $\vec{\nabla} \cdot \vec{F}$ of the vector field, as in Eq. (2):

$$\varrho_F = \vec{\nabla} \cdot \vec{F}. \tag{2}$$

In electrodynamics, the field $\vec{F}$ corresponds to the electric field $\vec{E}$ and the flux density ϱ_F is given by the charge density ϱ divided by the electric field constant ϵ_0, $\vec{\nabla} \cdot \vec{E} = \frac{\varrho}{\epsilon_0}$. Substituting the corresponding quantities for the electric field into Gauss's divergence theorem leads to Gauss's law of electricity in integral form (Eq. [3]):

$$\phi = \oiint \vec{E} \cdot d\vec{A} = \iiint \left(\frac{\varrho}{\epsilon_0}\right) dV = \frac{Q_{enclosed}}{\epsilon_0}. \tag{3}$$

The law shows that the net flux through a surface A surrounding a charge density ϱ depends only on the enclosed charge Q_{enclosed}. Knowing one of these two quantities allows us to deduce the other. However, this does not mean that one can easily use Eq. (3) to determine the electric field strength $\vec{E}$ in and around any charge distribution. Only if the charge distribution is highly symmetric (sphere, infinite cylinder, or infinite planar plate), the integral theorem may comfortably be used to determine the magnitude $|E|$ of the electric field (Singh, 2006).

In experimental physics problems, equipotential surfaces are placed in or around the charge distribution as a so called 'Gaussian' surfaces. Using the integral theorem to determine the electric field requires a smart choice of the Gaussian surface around the highly symmetric charge distribution. The following applies to these kinds of surfaces:

1. The magnitude of the electric field must be constant at the Gaussian surface, $\vec{E} = E(r) \cdot \vec{e}_r$ with $E(r) = const.$, and the field vector is perpendicular to the surface, $\vec{E} \parallel (\pm\, d\vec{A})$. Therefore,

$$\vec{E} \cdot d\vec{A} = E(r) \cdot dA. \tag{4}$$

2. However, if the field vector is parallel to the surface, i.e., perpendicular to the $d\vec{A}$, $(\vec{E} \perp (\pm d\vec{A}))$, the flux becomes zero:

$$\vec{E} \cdot d\vec{A} = 0. \tag{5}$$

The surface integral is simplified for equipotential surfaces to:

$$E(r) \cdot A_{equi} = \frac{Q_{enclosed}}{\epsilon_0}. \tag{6}$$

Students' Difficulties With the Application of Gauss's Law of Electricity

Various studies have shown that students struggle with the conceptual understanding of Gauss's law of electricity (Campos et al., 2023, 2025; Guisasola et al., 2008; Hernandez et al., 2023, 2025; Li & Singh, 2017;

Table 1. Categories of conceptual difficulties regarding symmetries, electric fluxes, and fields of charge distributions according to Singh (2006) and the references provided in

Category	Students' conceptual difficulties	ATS	
		OT	TS
Electric charge & flux are scalars	- The scalar product in Gauss's law of electricity (3) is misunderstood, so that it is thought that charge & flux are also vectors (Singh, 2006).	01	01
Electric field inside a hollow nonconductive object	- The properties of a hollow conductor are generalized to insulators: (1) Thinking that the electric field strength inside an insulator is zero everywhere (McDermott & Shaffer, 1992; Singh, 2006). (2) Thinking that an insulator can shield an external field (Campos et al., 2023; Hernandez et al., 2023; Pepper et al., 2010; Singh, 2006). - Confusion of the symmetry argument and superposition argument for charges (McDermott & Shaffer, 1992; Pepper et al., 2010; Singh, 2006)	07 10 10	24 25 25
Underlying symmetry of a charge distribution	- Reasoning based on the symmetry of the body instead of the symmetry of the charge distribution (Campos et al., 2021; Hernandez et al., 2023; Singh, 2006) - Thinking that any closed (also irregular) surface can be used as a Gaussian surface (Campos et al., 2023; Hernandez et al., 2025; McDermott & Shaffer, 1992; Pepper et al., 2010) - Incorrect applicability of Gauss's law for finite charged or irregular charge distributions (Campos et al., 2023; Pepper et al., 2010; Singh, 2006) - Objects are not simplified to a point charge in the center of the object when viewed from the outside (Singh, 2006)	05 06 09 10 5	10 11 22 25 10
Relationship between electric field and flux	- Wrong conclusion, that if $\phi = 0 \rightarrow \|E\| = 0$ at Gauss surfaces (Campos et al., 2023; Guisasola et al., 2008; McDermott & Shaffer, 1992; Pepper et al., 2010; Singh, 2006) - Confusion about the relationship of the e-field at the point on a surface and its contribution to the flux through this surface (Hernandez et al., 2023, 2025; Pepper et al., 2010; Singh, 2006) - Forgetting to consider the direction of the field lines (Guisasola et al., 2008; Singh, 2006) - Wrong idea that despite the same enclosed net charge the flux through different Gauss surfaces is different (Hernandez et al., 2023; Singh, 2006) - Despite knowing Q, think that only flux through symmetrical surfaces can be calculated (McDermott & Shaffer, 1992; Singh, 2006)	03 07 04 03 08	08 24 09 08 21
Relevancy of a closed Gauss surface	- Any (opened and closed) surface can be used for the surface integral of the Gauss law of the theory of electricity (Campos et al., 2023; Hernandez et al., 2023; McDermott & Shaffer, 1992; Pepper et al., 2010; Singh, 2006)	02 08 09	05 21 22
Principle of superposition	- Only the nearest charge to an observation point has an influence on the e-field at this observation point (Singh, 2006) - Only the perpendicular distance to the charge is considered (Singh, 2006) - Errors in vector addition to identify the net electric field (Campos et al, 2025)	10	25

Note. ATS: Associated tasks; OT: Our test; TS: Test by Singh (2006); & the two right columns on 'associated tasks' refer to the test items of the concept test described before

McDermott & Shaffer, 1992; Pepper et al., 2010; Singh, 2006).

According to Singh (2006), the conceptual difficulties can be divided into six categories summarized in the left two columns of **Table 1**. The most common difficulties refer to the symmetry of the charge distribution and the associated Gaussian surface (Campos et al., 2023; Hernandez et al., 2023; McDermott & Shaffer, 1992; Pepper et al., 2010; Singh, 2006), the relationship between electric field and flux (Campos et al., 2023; Guisasola et al., 2008; McDermott & Shaffer, 1992; Pepper et al., 2010; Singh, 2006) and the incorrect generalization of the concepts of closed conductors to insulators, respectively (Campos et al., 2023; Hernandez et al., 2023; McDermott & Shaffer, 1992; Pepper et al., 2010; Singh, 2006). When selecting the appropriate Gaussian surface to calculate the electric field strength of a charge distribution, students often struggle to distinguish between the symmetry of the charge distribution and the symmetry of the body (Campos et al., 2023; Hernandez et al., 2023; Singh, 2006). They mistakenly believe that Gauss's law of electricity applies to irregular charge distributions (McDermott & Shaffer, 1992; Pepper et al., 2010; Singh, 2006) and do not always realize that Gaussian surfaces must be closed and symmetric, with a shape that corresponds to the equipotential surfaces of the electric field (Campos et al., 2023; Hernandez et al., 2023; McDermott & Shaffer, 1992; Pepper et al., 2010; Singh, 2006).

When students discuss the flux through Gaussian surfaces and the electric field, they often draw incorrect conclusions. For example, they claim that if the flux through a surface is zero, the electric field at a point on the surface must also be zero (Campos et al., 2023;

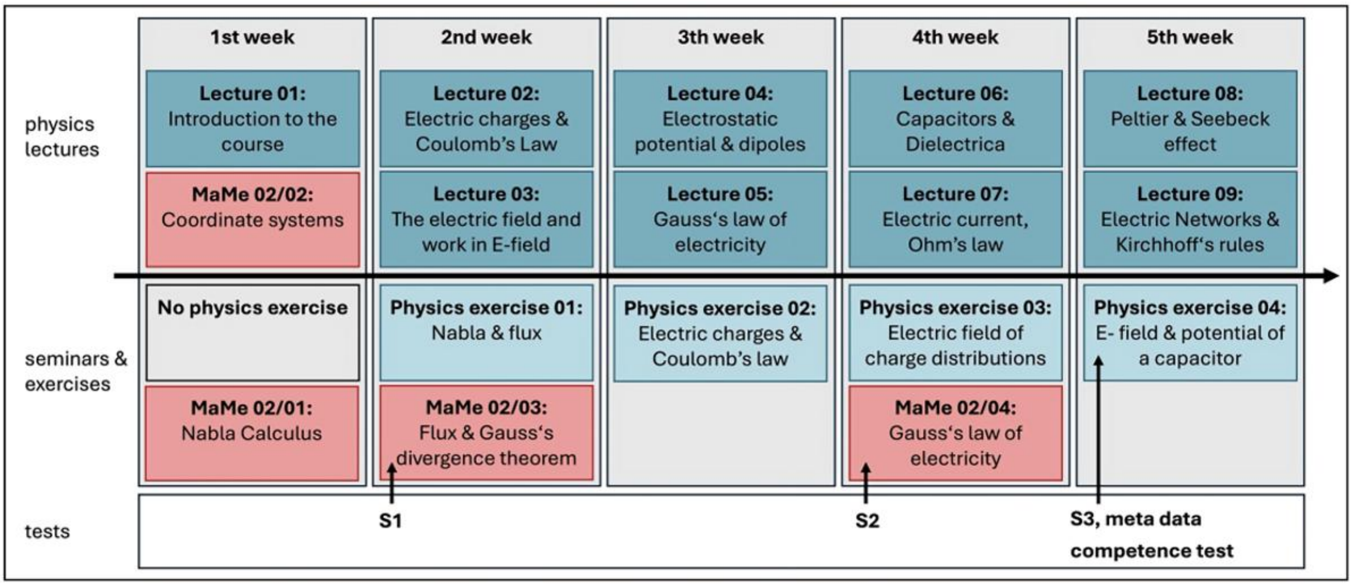

Figure 1. Timeline of the intervention on Gauss's law of electricity in the physics course (the physics lectures are displayed above, the supplementary MaMe seminars and physics exercises below the timeline & the timing of the three self-assessments [S1, S2, & S3] and the concept tests is visualized in the last row) (Source: Authors' own elaboration)

Guisasola et al., 2008; Hernandez et al., 2023; McDermott & Shaffer, 1992; Pepper et al., 2010; Singh, 2006), failing to recognize that the flux can become zero through the scalar product of an electric field perpendicular to the normal surface. They do not consider that a charge located next to the closed surface generates an electric field at a point on the surface, even though the flux through it becomes zero. A third major conceptual difficulty concerns the generalization of certain properties of conductors to insulators. For example, students conclude that the electric field must be zero at any point inside a closed insulator, and that an insulator can shield an external electric field in the same way as a conductor (Campos et al., 2023; Hernandez et al., 2023; McDermott & Shaffer, 1992; Pepper et al., 2010; Singh, 2006).

INTERVENTION

When planning teaching sequences on Gauss's integral theorem, it is therefore essential to take the commonly known conceptual difficulties (see **Table 1**) into account and address them during the teaching learning sequences. **Figure 1** shows the time schedule for the first five weeks of the electrodynamics course with the integrated blended learning mathematical methods seminars. The course consists of two 90-minute physics lectures per week, supplemented by weekly 90-minute physics exercises and fortnightly 45-minute mathematics methods (MaMe) seminars. The physics lecture starts with Coulomb's force, the electric field and the potential of point charges, before generalizing these concepts to charge distributions. Gauss's electricity law is introduced and interpreted in the physics lecture at the end of the third week. Consequently, Gauss's integral theorem must be introduced as a basis during the second week (MaMe 02/03, see **Figure 1**). The fourth week of the course is dedicated to practicing the application of Gauss's law of electricity by calculation of the electric field of different charge distributions (MaMe 02/04; physics exercise 03 and 04).

In the sense of a spiral curriculum, most of the components of Gauss's divergence theorem (e.g., nabla and volume element) are introduced in previous MaMe seminars on mechanics and electrodynamics with focus on other applications of these mathematical operations. A detailed description of the mechanics seminar contents can be found in Kämpf and Stallmach (2024b). In the first week of electrodynamics lectures, the most important knowledge on the Nabla operator (MaMe 02/01) and working in various coordinate systems (MaMe 02/02) are reviewed. For this purpose, a physics lecture is replaced by a MaMe seminar (see **Figure 1**). The mathematics input in the first week of the electrodynamics course provides a joint starting point for the further MaMe course. The MaMe seminar 02/03 introduces Gauss divergence theorem. Therefore, the physical quantity of flux is explained, before comparing two methods of calculating the flux through a closed surface, as described in Eq. (1). The MaMe seminar 02/04 builds on this knowledge by adapting Gauss's divergence theorem to the electric field, leading to Gauss's law of electricity.

The blended learning MaMe seminars consist of an initial self-study phase followed by an in-depth face-to-face seminar. For the self-study phase, students are provided with one to two interactive videos, a written summary and an interactive game map for individual practice (Kämpf & Stallmach, 2023, 2024a, 2024b; Kämpf et al. 2025a). The materials for the MaMe seminars are published on the teaching and learning platform

Moodle™ (Moodle Pty Ltd, 2025) of Leipzig University and are available via the link provided in the reference list (Kämpf et al., 2025b).

During the face-to-face seminars, students further deepen their knowledge by means of several physic application tasks. Each face-to-face MaMe seminar starts with a short quiz, followed by a self-assessment. The results of the self-assessment form the basis for customizing the MaMe seminars to meet the students' needs. At the same time, the results can be used to support and document the students' learning process. Our first research question (**RQ1**) addresses these self-assessments. Moreover, we are interested in what conceptual difficulties the teacher training students still have after our intervention. This leads to the second research question (**RQ2**).

RQ1. How does students' confidence develop with respect to their topic-related competencies across the course?

RQ2. To what extent are physics teacher training students able to cope with the topical concepts after instruction through the intervention?

METHODS

Study Design and Samples

In order to investigate the two RQs, a study was conducted in summer term 2025, parallel to the intervention described in the last section, in which the second-semester physics teacher training students, who attend the electrodynamics course, took part. The size of the cohort for our study is limited due to the small number of students in our physics teacher training program. At the end of the summer term 2025, 47 students were admitted to the exam. Approximately half of these students participated in the voluntary studies on the application of Gauss' law of electricity. Since all students participated in the lecture on electrodynamics for the first time, they had no prior knowledge referring to Gauss's law of electricity.

To address the **RQ1** on the evolution of students' confidence, three successive self-assessments (S1, S2, and S3) were conducted between weeks two and five of the course (see **Figure 1**). The number of participants in the survey corresponds to the number of students present in MaMe seminar 03 and seminar 04 ($N_1 = 26$ and $N_2 = 22$, respectively) and in the physics exercise 04 ($N_3 = 24$).

The **RQ2**, concerning the students' conceptual knowledge, was examined in the final physics exercise 04 (see **Figure 1**) using a concept test adapted from Singh (2006). The $N_3 = 24$ students present during the physics exercise 04 took part in this voluntary and anonymous test. At the end of the concept test, we collected data on the use of the teaching-learning offers in the course. The students stated that they used on average 85% of the digital materials provided for the intervention. In detail, 23 students of the cohort N_3 participated in at least three of the four physics exercises, and 21 watched all the MaMe explanatory videos on Gauss's divergence theorem and Gauss's law of electricity.

Instruments and Data Analysis

Data analysis on students' self-assessment (RQ1)

The three subsequent self-assessment tests S1, S2, and S3 were used to examine the development of students' confidence in their topic-related competencies (see **Figure 1**). The self-assessments were surveyed at the start of the face-to-face MaMe seminar on Gauss divergence theorem (S1), at the start of the face- to-face MaMe seminar on Gauss law of electricity (S2), and at the start of the fourth physics exercise (S3). These tests were designed to assess the students' self-conception on skills necessary for applying Gauss's divergence theorem and calculating electric fields in and around charge distributions. The test used a four-point rating scale (uncertain [1], rather uncertain [2], rather certain [3], and certain [4]). Each answer option is assigned a value from 1 to 4. To gain an impression of the students' overall self-assessment, the mean value μ and standard deviation σ are calculated in accordance with Sullivan and Artino (2013). The changes in the partially paired self-assessments between the first (S1) and last (S3) survey are examined using a Mann-Whitney U test (Guo & Yuan, 2017). The corresponding effect sizes are described by the biserial point-correlation coefficient r (Tomczak & Tomczak, 2014).

Data analysis on students 'conceptual knowledge (RQ2)

At the end of the intervention, students' conceptual understanding was assessed using a concept test, which we adapted from Singh (2006). This test has already been evaluated several times (Li & Singh, 2017; Singh, 2006) and contains 25 single-choice questions to assess the understanding of symmetry and Gauss's law of electricity. We selected ten of the 25 items for our test. These ten items cover the entire spectrum of widespread difficulties in **Table 1**. The incorrect answer options are assigned to the respective difficulties addressed in the last column of **Table 1**. Each item has five answer options. Analyzing the answers provides a good overview of the difficulties experienced by students after our intervention. The authors of this paper translated the test items of the English original (see Singh, 2006) into German for use in the German teacher training course. The applied test with its ten translated items can be found in **Appendix A**.

Since it is not possible to completely prevent students from guessing (Lord, 1964), the proportion of correct answers is calculated using a guess correction according

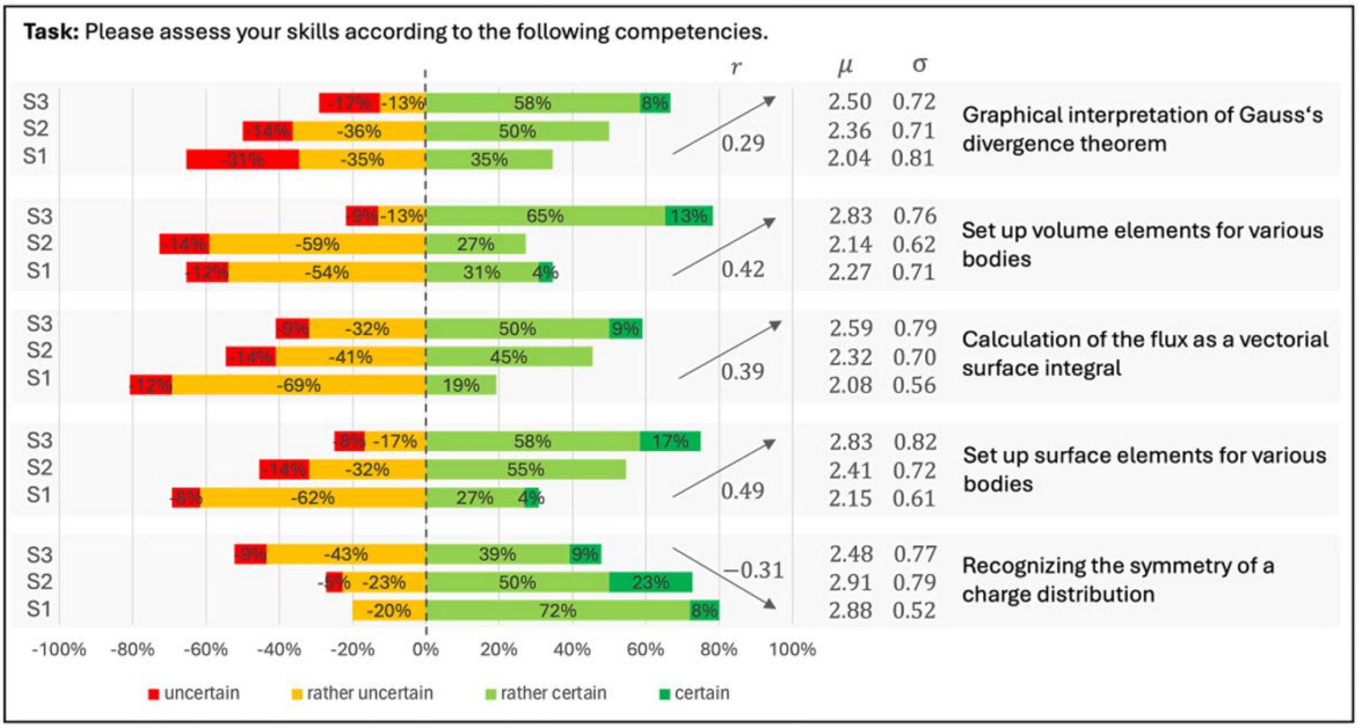

Figure 2. Students' self-assessment of five key competencies for applying Gauss's divergence theorem to calculate electric fields in and around charge distributions (the survey was conducted at three points during the intervention: S1 [$N_1 = 26$], S2 [$N_2 = 22$] and S3 [$N_3 = 24$], the arrows indicate rising and declining competencies as assessed by the test S1 and test S3, & the positive and negative values of the biserial point-correlation coefficient r indicate the effect sizes of the interventions) (Source: Authors' own elaboration)

to Pospeschill (2022). The guess-corrected value x_{corr} depends on the number of correct answers n_R, the number of incorrect answers n_F and the number of answer options k, see Pospeschill (2022):

$$x_{corr} = n_R - \frac{n_F}{k-1}. \quad (7)$$

The psychometric evaluation of the instrument through the lens of classical test theory (Bauer, 2015; Engelhardt, 2009) with respect to the item difficulty, the discriminatory index and the internal consistency resulted in the exclusion of the two item 1 and item 8. This leads to a reliability score of α = 0.50 for Cronbach's alpha. The psychometric properties of the full instrument are provided in **Table A1** in **Appendix A**. It shows a negative correlation for item 1 and item 8, which is the reason for excluding them in further data analysis.

RESULTS

Results of Students' Self-Assessment (QR1)

Figure 2 shows students' self-assessments of their confidences related to five necessary skills for the calculation of the electric fields inside and outside charge distributions applying to the Gauss's divergence theorem. Assessments that were uncertain or rather uncertain are shown to the left of zero, and assessments that were rather certain or certain are shown to the right of zero (Robbins & Heiberger, 2011). As the MaMe seminars focus on computation, this survey primarily refers to computational aspects.

Changes in self-assessment are illustrated by the value of the biserial point-correlation coefficient r and an associated arrow. The arrow points upwards for a positive and downwards for a negative effect size (see **Figure 2**). A positive trend in self-assessment can be seen across the upper four computational aspects. While after the first introductory video on Gauss's divergence theorem only 35% of students stated that they had a vague idea of what the integral theorem means graphically ($\mu_1 = 2.04$), at the end of the intervention 66% of students stated that they had a certain or rather certain idea of its graphical interpretation ($\mu_3 = 2.61$). The Mann-Whitney U test used to compare the results of S1 and S3 ($U[N_1 = 26, N_3 = 24] = 220, p = 0.056$) revealed a non-significant increase in self-assessment on the ability to graphically interpret Gauss's theorem during the intervention period. The biserial point-correlation coefficient $r = 0.29$ indicates a small-to-medium effect size of the intervention (LeBlanc & Cox, 2017). However, students became significantly more confident in setting up the surface element of the respective Gaussian surface ($U[N_1 = 26, N_3 = 24] = 158, p = 0.001$), in setting up the volume elements for respective Gaussian surfaces ($U[N_1 = 26, N_3 = 23] = 174, p = 0.007$) and in calculating the flux as a vectorial surface integral ($U[N_1 = 26, N_3 = 24] = 175, p = 0.011$). The biserial point-correlation coefficients of r = 0.49, 0.42

Table 2. Psychometric properties of the individual items: item difficulty, discrimination index, item-rest correlation, and adjusted Cronbach's alpha α_n (the Cronbach's alpha of the scale when the respective item n is not considered)

Item number	Item difficulty	Discrimination index	Item-rest correlation	$\overline{\alpha_n}$
2	0.92	0.08	0.41	0.42
3	0.29	0.17	0.11	0.51
4	0.67	0.25	0.61	0.27
5	0.54	0.17	0.16	0.49
6	0.50	0.13	0.25	0.45
7	0.08	0.04	0.15	0.51
9	0.13	0.13	0.30	0.44
10	0.21	0.08	0.03	0.53

and 0.39, respectively, indicate a medium-to-high effect size (LeBlanc & Cox, 2017).

However, a non-significant decrease in the self-assessment on recognizing the symmetry of charge distributions $(U[N_1 = 26, N_3 = 24] = 199, p = 0.041)$ from $\mu_1 = 2.88$ to $\mu_3 = 2.48$ was noted between the assessments of S1 and S3 (see **Figure 2**). While the first two self-assessments S1 and S2 to the topic of recognizing symmetries yield almost constant μ-values of $\mu_1 = 2.88$ and $\mu_2 = 2.91$, the third test resulted in a drop to $\mu_3 = 2.48$. This decline happened during week three and four, when Gauss's law of electricity was applied in physics exercises to investigate more difficult charge distributions and when the limitations of this law were discussed (see **Figure 1**).

Results of Students' Concept Test (RQ2)

Psychometric properties of the instrument

The item difficulty, together with other psychometric properties, i.e., discrimination and Cronbach's alpha of the instrument, are shown in **Table 2**. Lower item difficulty values indicate more difficult items. The criterion item difficulty is classified in the literature as 'excellent' for values between 0.2 and 0.8 (Jorion et al., 2015). The item 7 and item 9 of our survey tend to be 'too difficult' with a difficulty below 0.2.

Table 2 shows that a further evaluation of item 7 is required, because the item difficulty and discriminatory power are both outside the suggested ranges provided in **Table 3**. Nevertheless, item 7 offers valuable insight into students' misconceptions regarding the relationship between charge distributions and the effective electric field, as well as the properties of hollow conductors and insulators. The results and the interpretations of this item are too valuable to be removed from the test.

Cronbach's alpha was used to estimate the internal consistency, with a resulting value of α = 0.50, indicating a rather low internal consistency. However, this value can be considered acceptable since the test instrument consists of only eight items (Bauer, 2015; Bitzenbauer et al., 2024) and examines the heterogenous construct of concept knowledge (Edelsbrunner et al., 2025).

The quality of our test instrument was examined in accordance with classical test theory (Bauer, 2015; Engelhardt, 2009). **Table 3** summarizes the test's psychometric properties using the categorical judgement scheme 'excellent' to 'poor' of Jorion et al. (2015). The data in **Table 3** allow us to characterize the quality of our test instrument with respect to the five criteria given in the first column.

Table 3 is used to determine the criterion 'item difficulty' for the entire test. For this purpose, the item difficulties of the individual items (see **Table 2**) are assigned to the ranges of 'excellent', 'good', 'average' and 'poor' in the third row of **Table 3** (Jorion et al., 2015). The number of permitted outliers is shown in parenthesis. The 5 of the 8 items of our test fell into the required ranges for 'excellent' and 'good' test quality. However, due to the three outliers (items 2, 7, and 9) our test must be classified as 'good'.

Table 3. Categorical judgement scheme adopted from Jorin et al. (2015) (the number of items that can fall outside of this recommendation is indicated by the values in parentheses & the modified value for Cronbach's alpha suggested for scales of small length n is denoted by $\alpha^* = \alpha \cdot (n-1)/n$ in the last row) (see Bauer, 2015)

Criterion	Excellent	Good	Average	Poor	Our instrument (see text for further explanation)
Item statistics					
Difficulty	0.2-0.8	0.2-0.8 (3)	0.1-0.9	0.1-0.9 (3)	Good
Item number (see **Table 2**)	3, 4, 5, 6, 10	3, 4, 5, 6, 10 (2, 7, 9)	-	-	
Discrimination	> 0.2	> 0.1	> 0.0	> -0.2	Average
Item number (see **Table 2**)	4	3, 4, 5, 6, 9	2, 3, 4, 5, 6, 7, 9, 10	-	
Total score reliability					
α of total score	> 0.9	> 0.8	> 0.65	> 0.5	Poor (0.50)
α-with item deleted	All items less than overall α	(3)	(6)	(< 6)	Good
Item number (see **Table 2**)	2, 4, 5, 6, 9	2, 4, 5, 6, 9 (3, 7, 10)	-	-	
$\alpha^*(n = 8)$	> 0.79	> 0.70	> 0.57	> 0.44	Poor

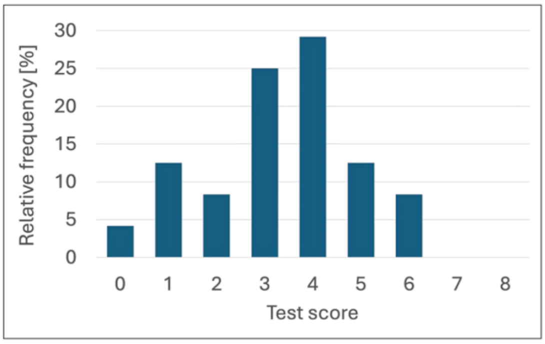

Figure 3. Distribution of students' test score (a maximum of eight points could be scored in the test) (Source: Authors' own elaboration)

According to Jorion et al. (2015), our test has an 'average' discrimination power since our eight test items have discrimination indices above 0.0 (see **Table 2**).

The simple Cronbach's alpha characterizes our test as 'poor' with respect to the internal consistency. The Cronbach's alpha value of concept tests with a short scale length (a small number of test items) can be adjusted using the formula $\alpha^* = \alpha \cdot (n-1)/n$ (see Bauer, 2015). This adjustment has not improved the internal consistency of our test. The low alpha value results from

(1) the short scale length and

(2) the examination of various sub-concepts (see **Table 1**), since the test is intended to provide a comprehensive overview of students' heterogenous concepts knowledge (Edelsbrunner et al., 2025).

Analysis of students' test responses

The distribution of the test results is shown in **Figure 3**. For the eight evaluated single-choice questions, the students could score a maximum of eight points. They achieved an average score of $\mu = 3.33$ points (median = 3.50) with a standard deviation of $\sigma = 1.58$. One student scored zero points, the best students scored 6 out of 8 points. 50% of the students answered at least half of the questions correctly. The asymmetrical distribution in **Figure 3**, which is shifted slightly to the left (i.e., none of the participants scored 7 or 8 points), suggests that the test instrument contains more difficult than easy questions and that students could not cope with a significant proportion of the items. Even the best students were not able to answer all questions of the test.

The distribution of responses to all items on the test instrument is shown in **Table 4**. To improve the test's internal consistency, items 1 and 8, highlighted in grey, were removed from further evaluation. The correct answers are highlighted in bold. The last column shows the rate-corrected proportions of the correct answers. By comparing the guess-corrected answers with the raw data, we were able to determine whether the students' guessing behavior influenced the proportion of correct answers. As the corrections for the eight evaluated tasks deviate by only 2–5% from the actual measured values (see **Table 4**), we can assume that students' guessing is negligible. Therefore, we base the discussion on the measured raw data.

The answer distribution in **Table 4** shows that item 2 was the only one answered correctly by 92% of students. Tasks 4, 5 and 6 were each answered correctly by at least 50% of students. Many incorrect answers were provided by the students for tasks 3, 7, 9, and 10. While a single incorrect answer option (d) was frequently selected in item 3, several different incorrect answer options were selected with approximately the same frequency for items 7, 9, and 10. In these three items, students had to verify the accuracy of two (item 10) or three statements (item 3 and item 7), respectively, and they had to identify all possible Gaussian surfaces of a charge distribution illustrated in a sketch (item 9). As shown in **Table 4**, some students recognized some of the correct statements, but only a small proportion recognized all of them.

DISCUSSION

Discussion of Students' Self-Assessment (RQ1)

Our aim was to address students' individual confidence and problems during the course through the self-assessment survey that accompanied the intervention. Initially, only 32% of students stated that they were at least rather confident with the graphical interpretation and the three major calculation steps required for solving physical problems in the application of gauss law of electricity. At the end of the intervention, 63% of students rated themselves as rather confident to confident. Our intervention achieved an important

Table 4. Percentage of students, who selected choices (a)-(e) on items 1-10 (the numbers in parenthesis are the corresponding item numbers in Singh [2006], the correct answers are highlighted in bold, the two tasks in grey (1, 8) are excluded from the evaluation, & the percentage of correct answers after deduction of the guess correction is shown in the last line)

Item number	01 (01)	02 (05)	03 (08)	04 (09)	05 (10)	06 (11)	07 (24)	08 (21)	09 (22)	10 (25)
(a)	63%	8%	4%	17%	17%	9%	21%	0%	**13%**	**21%**
(b)	38%	0%	**30%**	**67%**	0%	0%	21%	0%	25%	33%
(c)	0%	0%	9%	17%	25%	**52%**	33%	30%	21%	13%
(d)	0%	0%	52%	0%	**54%**	4%	17%	**39%**	21%	33%
(e)	0%	**92%**	4%	0%	4%	35%	**8%**	30%	21%	0%
Correct answers (x_{corr})	**53%**	**90%**	**26%**	**62%**	**52%**	**50%**	**6%**	**37%**	**10%**	**19%**

educational goal, the improvement of students' self-efficacy (Toggerson et al., 2020) for calculator skills. A high self-assessment of one's own competencies, and thus the belief that one is capable of completing a task, has been confirmed as a strong predictor of academic performance and ability in science (Britner & Pajares, 2001; Durk et al., 2020; Toggerson et al., 2020).

We observed a high level of uncertainty among students in recognizing the symmetry of charge distributions. By the end of the course, 43% of respondents stated that they were rather uncertain, and 9% stated that they were uncertain, which is consistent with the concept test results in subsubsection 5.2.2. In item 5 of the test, only 54% of respondents correctly identified two of the three charge distributions as symmetrical enough to apply Gauss's theorem (see **Table 4**). Likewise, in task 6, only 50% were able to assign both possible Gaussian surfaces in order to calculate the magnitude of the electric field of an infinite extended charged plate. Comparing the uncertain self-assessment of approximately 50% of the students with the 54% of incorrect answers regarding recognizing the symmetry of charge distribution highlights the link between self-assessment and performance (Britner & Pajares, 2001; Durk et al., 2020; Togger- son et al., 2020). The three self-assessments demonstrate that, following our blended learning scenario, students have grown in confidence in their ability to calculate using Gauss's law of electricity. However, there still remain gaps in conceptual knowledge as discussed in the following section.

Discussion of Students' Concept Test (RQ2)

Existing conceptual difficulties can be identified by analyzing the distribution of students' responses in the concept test provided to the students at the end of the intervention (test S_3). The incorrect answers are clustered according to the respective categories of conceptual difficulties described in the first column of **Table 1**.

Electric field inside a hollow nonconducting object

Item 10 examined the understanding of the electric field within an insulating, hollow body. 16 respondents (66%) incorrectly assumed that a closed hollow insulator could shield an external electric field. This high percentage suggests that the concept of the hollow conductor is wrongly transferred to insulators and thus incorrectly generalized (Singh, 2006). This conceptual difficulty was also obtained in preceding concept tests (Campos et al., 2023; Hernandez et al., 2023; Li et al., 2023; Pepper et al., 2010; Singh, 2006). For example, Singh's (2006) concept test done with two different cohorts of under graduated physics science students shows that 45% and 68% of the students, respectively, also wrongly generalized the shielding of an electric field by hollow conductors to hollow insulators.

The underlying symmetry of a charge distribution

Items 5, 6, and 9 tested the conceptual understanding about the symmetry of the charge distribution. Item 5 addressed the issue that students often consider the symmetry of the body rather than the charge distribution when deciding whether to apply Gauss's law of electricity to calculate the electric field. The majority of our students recognized that two of the three charge distributions could be treated as homogeneously charged spheres. Thus, these students correctly decided that Gauss's law of electricity may be applied to calculate the resulting electric field. However, seven students (29%) incorrectly concluded that the axial symmetry of the dumbbell was sufficient to apply Gauss's law. The wrong reasoning is based on the symmetry of the body instead of the symmetry of the charge distribution which was also found by Campos et al. (2023), Hernandez et al. (2023) and Singh (2006). For instance, the study by Singh (2006) specifies that 11% and 18% of respondents of two different cohorts gave the same incorrect answers.

Item 6 and item 9 addresses the conceptual difficulty that any closed surface can be used as a Gaussian surface (Campos et al., 2023; Hernandez et al., 2023; McDermott & Shaffer, 1992). In task 6, eleven students (48%) incorrectly answered that a sphere could also be used as a Gaussian surface for an infinitely extended charged plate. They failed to consider that the electric field and the surface normal of the Gaussian surface point in different directions on different parts of the sphere's surface. Similar difficulties arise for item 9, where students are asked to select a Gaussian surface for an infinitely long line charge. In line with Singh's (2006) research, our answers are almost uniformly distributed, indicating an uncertainty in selecting the appropriate Gaussian surface.

Relationship between electric field and flux

Item 3 and item 4 tested the understanding of the relationship between the electric field and the flux. Examining the incorrect answers to item 3 reveals a widespread conceptual difficulty. 12 students (50%) incorrectly concluded that a lower flux through a closed surface indicates a smaller electric field at points on the Gaussian surface. The charge and distance dependency of the electric field, as well as the pure charge dependency of the flux, were not recognized. Similar results have already been observed in several earlier studies (Campos et al., 2023; Guisasola et al., 2008; Hernandez et al., 2025; McDermott & Shaffer, 1992; Pepper et al., 2010; Singh, 2006). For example, in Singh's (2006) surveys, about 35% of wrong answers appeared evidencing the same conceptual difficulty.

Relevancy of a closed surface

Item 2 and item 9 addressed the prerequisite that Gauss's integral theorem only applies to closed Gaussian surfaces (Campos et al., 2023; Hernandez et al., 2023; McDermott & Shaffer, 1992; Pepper et al., 2010; Singh, 2006). In item 2, students were asked to select this requirement for a Gauss surface from five options. A remarkable proportion of 22 out of the 24 participating students (92%) were able to select the correct answer to this question. This suggests that they understood the concept of closed surfaces. In item 9, students were asked to identify a suitable Gaussian surface for an infinitely long line charge. Five respondents (21%) claimed that the flux could also be determined using a two-dimensional quadratic surface. Similar answer distributions can be seen in Singh's (2006) test, in which 18% and 15% of respondents respectively chose this incorrect answer. One possible explanation for this discrepancy is that students misread the task and did not recognize that a two-dimensional plane sheet does never surrounds a charge. Due to the high level of correctness in item 2, the concept of the closed surface can be considered as known, but its transferability to other geometries and symmetries is capable of improvement.

Comparison to Other Research Results

Singh (2006) conducted her concept test with large samples from various physics degree programs. She examined the conceptual knowledge of 541 students on the 'introductory calculus-based physics course' and 28 students of the 'upper-level undergraduate E&M course'. Both groups answered on average 49% of the items correctly. Our physics teacher training students, who attend an experimental physics lecture on electrodynamics in their second semester, answered on average of 45% of the items correctly. This means that the results for our teacher trainees are broadly comparable with those of bachelor's students in physics tested by Singh (2006). Similar trends can be seen in the answer distributions, showing which tasks were easy and which were difficult for the students. The fact that none of our students were able to answer all the questions correctly is consistent with Singh's (2006) finding that only two named students achieved the maximum score in her test. The difficulties experienced by our German physics teacher trainees are similar to those faced by American physics students, highlighting the importance of a didactic approach for teaching the Gauss law of electricity based on the difficulties discussed in the last section. We do not know the teaching format of the electrodynamics lectures in Singh's (2006). Nevertheless, it is plausible that the conceptual difficulties relating to Gauss's law are comparable internationally and across different physics courses.

Li and Singh (2017) published six tutorials based on the results of their concept test (Singh, 2006). In these tutorials, they introduce the topics of Coulomb's law, superposition, symmetry, electric field and flux, as well as Gauss's law for determining the magnitude of the electric field. After completing the tutorials, they examined 13 of the 25 test items in a comparative study. Students who attended the tutorials achieved an average test score of 54%, whereas the control group (who did not attend the tutorials) achieved an average score of 33%. Our course lies between the two extremes with an average test score of 45%. We know that we could not expect to achieve the same good results as Li et al. (2017) with our blended learning MaMe seminar approach on Gauss's law of electricity reported in Kämpf and Stallmach (2023, 2024a, 2024b) and Kämpf et al. (2025a). However, with our mathematics intervention integrated into the physics course at the right instant of time, which includes two accompanying mathematical methods seminars and thoughtful planned physics exercises, we achieved comparable results to those in bachelor's degree programs (Singh, 2006) and even better test results than the control group in Li and Singh (2017) attending a traditional electrodynamics lecture.

Limitations

This study offers an initial insight into the conceptual difficulties experienced by physics teacher trainees when applying Gauss's law of electricity. Due to the limited time associated with the mathematics education for physics teacher trainees at the authors university the interventions for all mathematical topics were carried out using a specially designed blended learning setup. The constraint in teaching time forced us to apply only a few selected items of the well-established instrument to test the conceptual knowledge to Gauss law of electricity. Please note that the instrument used in this study consists of only eight items in total. The small scale length of our test limits both the statistical significance and scopes of the contents covered. Consequently, it was possible to examine only a few, but not all the difficulties identified in previous publications on this topic (Campos et al., 2023; Hernandez et al., 2023; McDermott & Shaffer, 1992; Pepper et al., 2010; Singh, 2006)

Furthermore, we are aware that the small size of our physics teacher trainee cohort limits the statistical significance of our results with respect to transferring our findings to larger groups. However, any research on small and very specialized study programs will face similar constraints. The only choice we have is to work with exactly these small groups, study their learning difficulties and investigate their performances to improve our learning offers specifically and thus to support our students effectively.

As our test instrument only checks the answers to questions, we were not able draw conclusions on the students' cognitive processes initiated by our blended-learning intervention. To mitigate these limitations, future research combining our self-assessment approach with further empirical methods such as interviews and with pre- and post-tests would be beneficial.

CONCLUSION AND OUTLOOK

The article describes the design features and evaluation of a blended learning scenario on Gauss's divergence theorem and Gauss's law of electricity for physics teacher training students. Our course combines a traditional physics lectures with interlinked physics exercises and blended learning MaMe seminars.

Throughout the course, students grew in their confidence with respect to their ability to use Gauss's law of electricity to calculate the magnitude of the electric field of charge distributions. However, after our intervention students still have conceptual difficulties regarding their recognition of the symmetries of charge distributions, the generalization of the conductive sphere principle to insulators, and the relationship between electric field and flux.

Therefore, four pedagogical implications have emerged as particularly important for future practice:

1. The vector field and its flux must be clearly distinguished from each other, and their relationship must be addressed more frequently. In our revision, we will set a first application task on the flux and magnitude of a planet's gravitational field through different Gaussian surfaces in physics exercise 01 (see **Figure 1**). Because the students are familiar with the gravitational field from the previous mechanics lecture, this link may help understanding the relationship between field and flux. Similar tasks on charge distributions will be revisited later.
2. Conductors and insulators must be more clearly distinguished in terms of their properties when an external field is applied. Direct comparisons can be improved by conducting experiments observing the shielding of the electric field by various conductors or insulators.
3. The distinction between the symmetry of a charge distribution and the symmetry of a body should be demonstrated using several examples. In future, we will provide more examples of situations in which the symmetry of the body does not correspond to that of the charge distribution. We will discuss for which types of charged bodies Gauss's law is applicable.
4. A strong interplay between formal and conceptional aspects of Gauss's law is important to trigger a global view on Gauss's law of electricity. We recommend adding a sub-task about sketching the vector field based on the symmetry of the charge distribution to all formal calculation tasks. This may stimulate a deeper reflection about formal and conceptional aspects.

Our intervention and the presented research are built upon Singh's (2006) and Li and Singh's (2017) works investigating concepts related to Gauss's law of electricity. We are adding the results of second-semester physics teacher training students to their samples of physics students from different semesters. After the blended learning intervention our teacher training students achieve comparable results to Singh's (2006) undergraduate physics students.

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AI statement: The authors stated that generative AI tools (e.g. DeepL Write) were only used to check the clarity of the manuscript in English. No content was generated by AI.

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APPENDIX A

Items of the Concept Test for RQ2 Translated into German

For the use in the German course of physics teacher trainees at Leipzig University, the 10 items of the concept test to investigate **RQ2** were translated from their original versions in English language (see Sing, 2006) into German. The item numbers 1 to 10 of the German concept test which is printed below correspond to equivalent items from Singh's (2006) test. **Table 1** provides the assignment of the corresponding item numbers. Figures (as in items 4, 5, 6, 7, 8, and 10) were taken from the original without changes and are not included here.

The concept test was carried out anonymously. It was only evaluated if the participants had given their consent (see very first item not labelled with a number).

Psychometric Data of the Concept Test

Table A1 provides the psychometric properties of the ten individual items of the concept test without excluding item 1 and item 8 as in **Table 2**. The value of Cronbach's alpha is 0.04 if all 10 items are considered. It improves to 0.5 if the item 1 and item 8 with the most negative item-rest correlations are removed from data evaluation.

Table A1. Psychometric properties of all 10 individual items of the test (item difficulty, discrimination index, item-rest correlation, and adjusted Cronbach's alpha [α_n] [the Cronbach's alpha of the scale when the respective item *n* is not considered] & Cronbach's alpha value is therefore 0.04)

Item number	Item difficulty	Discrimination index	Item-rest correlation	$\overline{\alpha_n}$
1	0.63	0.00	-0.22	0.21
2	0.92	0.08	0.21	-0.06
3	0.29	0.17	0.13	-0.06
4	0.67	0.25	0.52	-0.46
5	0.54	0.17	0.05	0.00
6	0.50	0.13	0.07	-0.01
7	0.08	0.04	-0.06	0.07
8	0.38	-0.04	-0.43	0.34
9	0.13	0.13	0.24	-0.10
10	0.21	0.08	0.05	0.08

Concept Test With Its 10 Single Choice Items (in German Language)

Declaration of consent and item 1 to item 4

Konzepttest Satz von Gauß

○ Ich erkläre mich damit einverstanden, dass im Rahmen der Lernwirksamkeitsstudie des Flipped Classroom Modells der MaMes Daten in **anonymisierter Form** erhoben und ausschließlich für wissenschaftliche Zwecke weiterverbreitet werden.

Bei den folgenden Fragen ist jeweils EINE Antwort richtig.

① Wählen Sie alle Größen, die Vektoren sind.
(i) Elektrisches Feld; (ii) Elektrischer Fluss; (iii) Elektrische Ladung

○ nur (i)
○ (i) und (ii)
○ (i) und (iii)
○ (ii) und (iii)
○ (i), (ii) und (iii)

② Damit das Gaußsche Gesetz gültig ist, MUSS die verwendete Gauß-Fläche (Fläche, durch die wir den Fluss detektieren) eine ...

○ hochsymmetrische Fläche sein.
○ Kugel sein.
○ zylindrische Oberfläche sein.
○ offene Oberfläche sein.
○ geschlossene Oberfläche sein.

③ Dein Freund misst den Fluss durch drei geschlossene Oberflächen (1), (2) und (3).
$\phi_1 = 1\frac{Nm^2}{C}$, $\phi_2 = 2\frac{Nm^2}{C}$ und $\phi_3 = -3\frac{Nm^2}{C}$.
Wähle alle Aussagen, die man aus der Messung ableiten kann.

(i) Die Oberfläche der Fläche (3) ist am größten.
(ii) Die Nettoladung, die in der Oberfläche (3) eingeschlossen ist, ist am größten.
(iii) Das elektrische Feld ist auf der Oberfläche (1) überall schwächer als auf der Oberfläche (2).

○ nur (i)
○ nur(ii)
○ (i) und (ii)
○ (ii) und (iii)
○ (i), (ii) und (iii)

④ Im Bild sind drei konzentrische kugelförmige Gaußsche Flächen A, B und C dargestellt, in deren Zentrum sich eine positive Punktladung +Q befindet. Eine zweite, aber negative Punktladung -Q wird nur von der Fläche C eingeschlossen.

Welche Aussage über die Größenordnung des elektrischen Flusses durch die drei Flächen ist richtig?

○ $\phi_A = \phi_B = \phi_C$
○ $\phi_A = \phi_B > \phi_c$
○ $\phi_A > \phi_B > \phi_C$
○ $\phi_B > \phi_A > \phi_C$
○ Keine der Aussagen.

Figure as in corresponding item of Singh, C. (2006)

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Figure A1. Declaration of consent and item 1 to item 4 (Source: Original test by Sing, 2006; German translation and typesetting by the authors)

Declaration of item 5 to item 7

Konzepttest Satz von Gauß

⑤ Im Bild sind 3 Isolatoren gezeigt, bei dem jeweils die mit „+“ gekennzeichneten Körper homogen geladen sind. Die ungeladenen Teile sind nicht polarisierbar.

Wählen Sie alle folgenden Fälle aus, für die das elektrische Feld an jedem beliebigen Punkt außerhalb des Objekts **leicht** aus dem Gaußschen Gesetz berechnet werden kann.

Figure as in corresponding item of Singh, C. (2006)

- ○ nur (i)
- ○ nur (ii)
- ○ (i) und (ii)
- ○ (i) und (iii)
- ○ (i), (ii) und (iii)

⑥ Im Bild ist eine unendlich große homogen geladenen Platte und drei mögliche Gaußsche Flächen: eine Kugel, ein Würfel & ein Zylinder. Der Punkt A befindet sich in der oberen Mitte jeder Gaußschen Fläche. Für welche der Gaußschen Flächen lässt sich mit Hilfe des Gaußschen Gesetzes das elektrische Feld im Punkt A **leicht** berechnen?

Figure as in corresponding item of Singh, C. (2006)

- ○ Nur die Kugel ist symmetrisch genug.
- ○ Nur der Zylinder, denn durch die Seitenwände gibt es keinen Fluss und er hat eine kreisförmige Symmetrie.
- ○ Nur der Zylinder und der Würfel, denn jede Form, bei der die Seitenwände recht-winklig zur Platte und die Deckfläche parallel zur Platte verlaufen, funktioniert.
- ○ Nur die Kugel und der Zylinder, weil sie einen kreisförmigen Querschnitt haben.
- ○ Alle Flächen funktionieren, da sie symmetrisch sind.

⑦ Im Bild sind vier Regionen A, B, C und D (getrennt durch kugelförmige Oberflächen) dargestellt. Das elektrische Feld ist in den Regionen A (innerste Region) und D (äußerste Region) gleich Null. Das elektrische Feld in den Regionen B und C ist radial nach außen bzw. nach innen gerichtet.

Figure as in corresponding item of Singh, C. (2006)

Wähle alle richtigen Aussagen.

(i) Die kombinierte Nettoladung, die in allen dargestellten Regionen eingeschlossen ist, muss Null sein.

(ii) Im Zentrum der Region A kann es **keine** Punktladung geben.

(iii) Zwischen den Regionen B & C muss eine negative Oberflächenladung sein.

- ○ nur (i)
- ○ (i) und (ii)
- ○ (i) und (iii)
- ○ (ii) und (iii)
- ○ (i), (ii) und (iii)

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Figure A2. Declaration of item 5 to item 7 (Source: Original test by Sing, 2006; German translation and typesetting by the authors)

Declaration of item 8 to item 10

Konzepttest Satz von Gauß

⑧ In Bild sind vier imaginäre geschlossene Flächen dargestellt, die koaxial zu einer isolierten, unendlich langen Ladungslinie (mit einheitlicher linearer Ladungsdichte λ) liegen. Wählen Sie alle Flächen aus, durch die der elektrische Nettofluss gleich $\phi_S = \frac{\lambda L}{\epsilon_0}$ ist.

Figure as in corresponding item of Singh, C. (2006)

- ○ nur (i)
- ○ (i) und (ii)
- ○ (i) und (iii)
- ○ (i), (ii) und (iii)
- ○ (i), (ii), (iii) und (iv)

⑨ Wir bleiben bei der selben Anordnung wie in der letzten Aufgabe. Wählen Sie alle Flächen aus, die als Gauß-Flächen verwendet werden können, um die Größe des elektrischen Feldes an einem Punkt P auf der Fläche mit Hilfe des Gaußschen Gesetzes **leicht** zu bestimmen:

- ○ nur (i)
- ○ (i) und (ii)
- ○ (i) und (iii)
- ○ (i), (ii) und (iii)
- ○ (i), (ii), (iii) und (iv)

Figure as in corresponding item of Singh, C. (2006)

⑩ Im Bild befindet sich eine Punktladung +Q in der Nähe einer dünnen, isolierenden (nichtleitenden) Hohlkugel mit dem Radius L. Auf der Kugeloberfläche ist die gleiche Menge an Ladung+Q gleichmäßig verteilt. Keine anderen Ladungen sind in der Nähe. Welche der Aussagen über das **elektrische Feld in den Punkten A** (Mitte zwischen Punktladung & Mittelpunkt der Hohlkugel) und **B** (innerhalb der Hohlkugel) ist richtig?

Figure as in corresponding item of Singh, C. (2006)

- ○ Das elektrische Feld ist im Punkt A gleich Null, jedoch im Punkt B ungleich Null.
- ○ Das elektrische Feld ist im Punkt A ungleich Null, im Punkt B gleich 0.
- ○ Das elektrische Feld ist in beiden Punkten A und B ungleich Null.
- ○ Das elektrische Feld ist in beiden Punkten A und B gleich Null.
- ○ Es ist unmöglich, diese Frage zu beantworten, ohne den Zahlenwert von Q zu kennen.

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Figure A3. Declaration of item 8 to item 10 (Source: Original test by Sing, 2006; German translation and typesetting by the authors)

Self-Assessment Test Handed Out to the Students (in German)

Konzepttest Satz von Gauß

Schätzen Sie Ihre Kompetenzen ein.

	unsicher	eher unsicher	eher sicher	sicher
Vorstellung, was der Integralsatz von Gauß aussagt	○	○	○	○
Volumenelemente aufstellen	○	○	○	○
Flächenelemente aufstellen	○	○	○	○
Den Fluss als vektorielles Oberflächenintegral berechnen	○	○	○	○
Die Symmetrie von Ladungsverteilungen erkennen	○	○	○	○
Zwischen elektrischer Ladung, elektrischen Feld und Fluss unterscheiden	○	○	○	○
Äquipotentialflächen in elektrischen Feldern auffinden	○	○	○	○
Anhand der Ladungsverteilung erkennen, ob es einfach ist, das Gaußsche Gesetz zur Bestimmung des elektrischen Feldes zu nutzen	○	○	○	○
Das elektrische Feld innerhalb von Ladungsverteilungen bestimmen	○	○	○	○
Die Überlagerung (Superposition) des elektrischen Feldes mehrerer Ladungen erkennen	○	○	○	○

Welche Angebote haben Sie genutzt?

○ MaMe Videos zum Seminar 03 *(Einführung Fluss & Integralsatz von Gauß)*
○ Präsenzseminar 03 *(Herleitung Gravitationsfeld in & um homogene Planeten)*
○ MaMe Videos zu Seminar 04 (*E-Feld in und um eine homogen geladene Kugel)*
○ Präsenzseminar 04 (*E-Feld in und um einen homogen geladenen unendlich langen Zylinder)*
○ min. 3 der letzten 5 Physikübungen

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Figure A4. Self-assessment test handed out to the students (in German) (Source: Authors' own elaboration)