SUPPORTING STUDENT LABORATORY EXPERIMENTS WITH AUGMENTED REALITY EXPERIENCE

Hallmann, Jona;
Stechert, Carsten;
Ahmed, Syed Imad-Uddin

Ostfalia University of Applied Sciences

ABSTRACT

The large availability of powerful mobile devices, such as smartphones or tablets, enables the location-independent use of augmented reality (AR) technology for various application areas with considerable added value. For example, AR experiences can be used to support students in laboratory courses during experiment preparation and execution to ensure a safe process and significantly improve the learning success. In addition, digital learning success controls can be realized with the extension of a database connection. In this paper, an AR-experience for the experiment of standing transverse and longitudinal waves is developed for the laboratory course of experimental physics. Finally, the effectiveness is tested with an evaluation by the students.

Keywords: Education, Evaluation, Case study

Contact:
Stechert, Carsten
Ostfalia University of Applied Sciences
Germany
c.stechert@ostfalia.de

Cite this article: Hallmann, J., Stechert, C., Ahmed, S. I.-U. (2023) 'Supporting Student Laboratory Experiments with Augmented Reality Experience', in *Proceedings of the International Conference on Engineering Design (ICED23),* Bordeaux, France, 24-28 July 2023. DOI:10.1017/pds.2023.324

1 INTRODUCTION

The rapid pace of innovations on multiple fronts is propelling the implementation of new technologies such as augmented reality (AR) technology. This is, in part, due to the easy availability of mobile devices with sufficient computational power to facilitate the location-independent use of AR technology. One area of application is to use AR technology to support student learning in a university setting (Orsolits and Lackner, 2020). At Ostfalia University of Applied Sciences, several lecture courses in the mechanical engineering department have already been supplemented with AR experiences to significantly enhance the learning experience of students. The extension of two-dimensional scripts with AR technology to a third and fourth dimension takes learning to a higher level of competency, which promotes type-dependent learning and enhances the appeal of lectures (Yengui et. al., 2021). Furthermore, laboratory courses can also benefit tremendously from the progress of AR technology and support students in preparing and conducting their laboratory experiments. In the first instance, the focus is on the laboratory for experimental physics, which is a required laboratory for students in their second semester of study who are working towards a bachelor in mechanical engineering. In this laboratory, students perform six different experiments in mechanics, optics, modern physics as well as vibrations and waves. In this paper, the AR experience was applied to one laboratory experiment involving mechanical waves: "Determination of the propagation velocity of standing transverse and longitudinal waves". Using the PTC tool chain, an AR-based teaching augments existing laboratory documentation to support students during the preparation as well as execution phase of the experiment. With this approach, certain misconceptions and problems arising during execution can be reduced or avoided entirely. In addition, by integrating the AR experience with a yet to be linked database, the grading of completed laboratory experiments can be facilitated. In this study, students assessed the AR experiences for their learning impact and their acceptance of this approach.

2 STATE OF THE ART

This section begins by describing the basics of augmented reality (AR) technology. Subsequently, the use of AR applications in education is explained by way of an example. The chapter concludes with a presentation of possible uses of AR in experiments.

2.1 Augmented reality basics

In AR, virtual objects are superimposed onto the real world. In this manner the real world is not replaced, but provided with additional digital information (Azuma, 1997). For the definition of AR technology, literature mainly refers to the three characteristic features, as defined by R. T. Azuma in 1997 (Lang and Müller, 2020). According to this, an AR system combines reality and virtuality, interacts in real time and registers the virtual contents in three-dimensional space (Azuma, 1997). The combination of reality and virtuality is realized by overlaying the real environment with virtual content. The digital enrichment can be so close to reality that the AR user can no longer distinguish between real and virtual impressions. If the viewer influences the supplemented virtual content through user interaction, for example by starting an animation, this is referred to as real-time interaction. With the third characteristic of an AR system, Azuma refers to the registration of the digital additions in the real world. When the user's perspective changes, the virtual objects behave like real objects, i.e. they have an apparently fixed place in reality (Doerner et al., 2022). For the purpose of comparison or differentiation with virtual reality, the two technologies - augmented reality and virtual reality - are classified under the generic term mixed reality (MR) in a reality-virtuality continuum (Grothus et al., 2021). In virtual reality, the user is in a computer-generated, virtual environment. The continuum established by Milgram and Kishino in 1994 extends between two extremes. The extreme point on the left describes reality, i.e. scenarios in a real environment. On the right side of the reality-virtuality continuum is the complete virtual environment (Lang and Müller, 2020). Within these extreme points, the mixed reality continuum describes the combination of real and virtual objects. Depending on the weighting of the proportions of real and virtual objects, the terms augmented reality and virtual reality are classified within this spectrum (Milgram et al., 1994). The proportion of reality decreases continuously from left to right, as shown in Figure 1 (Doerner et al., 2022). Augmented reality is, therefore, located on the left-hand side of the spectrum since the real part is predominant and is only supplemented with digital information. Virtual reality, on the other hand, is

https://doi.org/10.1017/pds.2023.324 Published online by Cambridge University Press

on the right of the continuum since the VR user is in an almost completely computer-generated environment. Thus, based on the combination of reality and virtuality and its weighting, the two technologies can be distinguished from each other within this spectrum (Milgram et al., 1994).

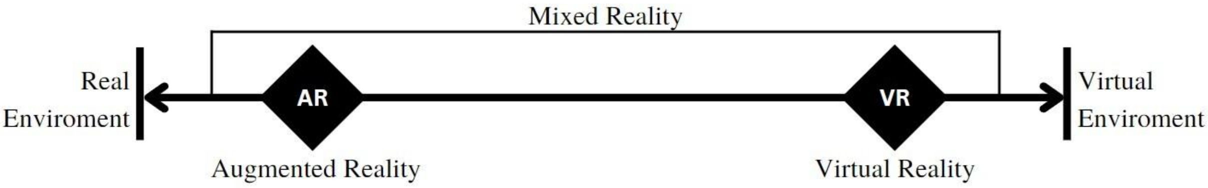

Figure 1. Reality-Virtuality-Continuum (Milgram et al., 1994)

2.2 Augmented reality for learning

The application possibilities and realization alternatives of AR technology are very diverse (Doerner et al., 2022). In sectors such as marketing, industry or gaming, AR applications are already being used on a daily basis. The intended use of augmented reality is already implemented in industry for some maintenance and repair tasks. Service technicians, for example, use the technology to enrich the real environment with helpful digital information, which has several advantages. Due to the constantly changing work environment and objects, a broad knowledge base is needed. In the past, several manuals were carried around, which made for an inflexible and tedious information management. All of this information can now be stored digitally and opened during work using mixed reality headsets. This not only saves money, but also time. Furthermore, the additional digital information provides increased safety during critical maintenance tasks (Hamadou et al., 2004).

For this paper, the field of education, i.e. training scenarios, is of particular importance. Training based on an AR experience allows for the further training of employees and learners without the need for additional capacity. In addition to saving time and money, the training units become more efficient because the training can be specifically adapted to the respective use case. Furthermore, employees are offered more safety at work, as the additional digital information can protect against beginner's mistakes. The high cost and time expenditure of preparation, i.e. the creation of 3D content and courses, describes the greatest challenge in the introduction of AR applications (Hanafi et al., 2020). The following is a selection of examples of the use of AR in education. At Ostfalia, AR technology is also used in the basic lecture on machine elements to better convey content regarding bearings, clutches, gears and complete gearboxes. For example, in this lecture an AR experience shows the differences between a straight-toothed and a helical-toothed gear and visualizes the resulting forces. With integrated comprehension questions, students can check their current level of knowledge. Students are thus enabled to continue their education with the AR experience regardless of location and time (Chlebusch et al., 2020). AR can also be used to teach historical content. At National Taiwan University, the two-dimensional teaching materials of the computer history lecture were supplemented with videos that can be accessed by students using video see-through technology. In this process, the printed images of historical figures from the field of computer networks are enriched with digital content. The use of the technology enhanced the students' attitude towards learning and helped in better understanding the subject (Hsu et al., 2015). Another example of the use of AR in education is shown by Alvarez-Marin and Velazquez-Iturbide (Alvarez-Marin and Velazquez-Iturbide, 2021). In this study, students are assisted by digital augmentation in calculating the volume of earth needed to build a road. The 2D information of the script is supplemented with virtual representations of a mountain before the construction and after the construction of the road in order to visualize and estimate the required earth volume in three dimensions.

2.3 Augmented reality for experiments

The use of AR experiences also offers an advantage in the preparation, implementation, and follow-up of scientific experiments. During preparation, the AR technology can motivate students to familiarize themselves more intensively, represent the real experimental setup three-dimensionally as opposed to existing two-dimensional laboratory documents in paper form, and visualize any hidden effects (Hanafi et al., 2020). Through additional integration of knowledge queries, the AR users can independently check their own level of competence. The best possible preparation subsequently save time during familiarization with the real experimental set-up on the day of the experiment and minimization of sources of error. In addition, AR can be used to enrich the real experiment with digital content in order to continue to support the students during the implementation phase and to enable a new type of engagement with technical content (Arnold et al., 2021). In this way, questions and errors can be further minimized, time and costs can be saved and the students' understanding of the experiment and the underlying theory can be improved. In the follow-up, AR can support, for example, the creation of diagrams and the filling of knowledge gaps. The use of future-oriented technology was particularly popular during the Corona pandemic. AR technology also made it possible to conduct laboratory sessions from home. For example, Chu (Chu, 2022) developed an application to conduct the electrical machines lab for engineering students. In this work, the students examine the behaviour of direct and alternating current machines under various load attributes. Among other things, torque, speed, current and voltage are noted. In addition, the use of AR not only enables distance learning, but also ensures the safety of the students, as they then do not come into contact with possibly defective equipment.

3 TARGET SETTING

In this section, the current problems in the laboratory for experimental physics at the Ostfalia University of Applied Sciences in Wolfenbüttel are first listed. This forms the basis for formulating the objectives for the AR experience.

3.1 Current issues in the laboratory

The examination for completion of the experimental physics laboratory consists of the submission of six experimental reports and a final oral examination. While of the participants are motivated and committed, in the past semesters the laboratory supervisors repeatedly received reports with numerous errors that, together with the results of the final oral examination, points to a lack of understanding concerning the performance of the experiments as well as their underlying physical principles. This problem can be traced, in part, back to limitations in the presentation of physical effects in the laboratory, insufficient preparation before coming to the laboratory and performing experiments under time pressure.
Prior to carrying out the experiment on standing waves, students are provided with a laboratory document containing descriptions and illustrations of the underlying physical principles, the experimental set-up and the experimental procedure via the learning platform StudIP. The preparation based on this is often insufficient, which leads to a large loss of time on the day of the laboratory experiment is performed. Many student groups first must familiarize themselves extensively with the experimental set-up and then compensate for the lost time by reducing the number of measurements or not evaluating the measurements in the laboratory itself. Consequently, faulty measurements can no longer be repeated. Furthermore, some students lack the necessary competence for abstraction to transfer the acquired basic knowledge from the two-dimensional documents to the real technical experiment, so that no deeper understanding can be acquired even during execution of the experiment. For example, physical effects that occur are difficult to recognize because functional variables are often not directly visible. Furthermore, the two attending laboratory supervisors have to manage six different experiments per laboratory session simultaneously, which, for a group of four students per group, amounts to twenty-four students per session. It is simply not possible for the supervisors to control each group closely. Consequently, some errors while performing the experiment slip through and some queries from students remain unanswered. The current didactic concept of the laboratory event for the lecture on experimental physics, with the included experiment on standing waves is to be expanded in the future using AR experiences.

3.2 Resulting objectives

The basic aim of this paper is the development of an AR experience for the laboratory experiment: "Determination of the propagation velocity of standing transverse and longitudinal waves" of the laboratory for experimental physics. Currently occurring problems during the laboratory performance are to be improved or even eliminated using AR technology. The existing real two-dimensional laboratory documents is to be supplemented by digital information within the AR experience to improve student understanding of the underlying physical principles and the experimental setups and to support the proper execution of the experiments. In addition, the experience is to be linked to a database so that the laboratory supervisors can read out the students' answers to comprehension questions or the inputs of set parameters. The user interface is to be equipped with programmed buttons. Using these buttons, users can interact with the teaching material. One example is by starting animations or displaying additional information. This encourages students to actively participate in the learning process. The AR experience is not intended to be a detailed visual step-by-step guide for conducting the experiment, but rather to encourage thorough preparation, point out special features in the experiment set-up and support the experimental execution with input options and written instructions. The AR experience is created with the PTC tool chain so that it can finally be called up via a "ThingMark" in connection with the "Vuforia View" application. The students are, thus, enabled to acquire the necessary understanding for the upcoming laboratory appointment independent of location and time and then to implement a proper execution of the experiment.

4 CREATION OF THE AR EXPERIENCE FOR THE EXPERIMENT

In this section, the AR experience is developed to transmit information about the experiment in the best possible manner. The section begins with a theoretical background of the experiment followed by a description of the experiment. Subsequently, a concept for the implementation of knowledge transfer with the help of AR technology is established. The AR experience is finally oriented on the basis of this concept.

4.1 Theoretical background of the experiment

A vibration or oscillation is a periodic change of a certain quantity as a function of time by an individual element capable of oscillation. In mechanics, a mass connected to a spring is a classic example of a system capable of mechanical oscillations. By pulling the mass connected to the spring, the mass will oscillate back and forth. The position of the mass, or its deflection, is a function of time. The maximum deflection is termed the amplitude. The time taken for a complete oscillation is the period of oscillation, while the number of oscillations per second is called the frequency. Waves result from the propagation of an oscillation in space and time due to coupling of a system of oscillators. When waves propagate freely through space, they transport energy, not matter. The propagation speed of a wave is given by its frequency multiplied by its wavelength (which is a distance between two oscillators having the same phase, or position in the oscillation). Waves are classified as transverse waves when the oscillation and propagation directions are perpendicular to one another. A classic example is the wave generated by oscillating one end of a rope. In cases where the oscillation and propagation direction are parallel to one another, they are termed as longitudinal waves. This is the case with sound waves. Waves can interfere with each other. This interference is governed by the superposition principle (Tipler and Mosca, 2019). As a result, waves travelling in one direction under certain circumstances can result in amplification or constructive interference. Another possibility is a reduction or even a cancellation effect, called destructive interference. The propagation of waves can also be confined spatially when the coupled oscillating elements are restricted in some manner. In the two-dimensional case, for example, the system of oscillators can be fixed at one end, or it can be open ended. In the former case, the oscillator at the fixed end cannot move, while in the latter case the oscillator at the end can deflect back and forth. A spatially confined wave propagating in one direction will reflect at a fixed end with a phase jump of pi or will reflect at an open end with no phase jump. Upon reflection the wave with travel in the opposite direction. The two waves interfere with one another. In case of spatial confinement, this process leads to the formation of standing waves consisting of nodes, which are locations with zero deflections and antinodes in which the deflections are at a maximum. In case of standing waves, no energy is transported due the spatial confinement of the waves. Standing waves can be generated using transverse as well as longitudinal waves.

Figure 2. Transverse standing waves

https://doi.org/10.1017/pds.2023.324 Published online by Cambridge University Press

4.2 Experiment description

The task of experiment: "Determination of the propagation speed of standing transverse and longitudinal waves" comprises of three main tasks. With the experimental set-up shown in Figure 3 on the left, the students have to determine the propagation speed of standing transverse waves generated on a cord. With the experimental set-up, as shown on the right of Figure 3, the propagation speed of standing longitudinal waves of a helical spring has to be determined. In addition, students have to investigate the effect of spring tension on the propagation speed or wavelength. The results have to be evaluated and interpreted in an experimental report. For preparation, only two-dimensional laboratory documents with descriptions and illustrations of the experiments are currently available to the students.

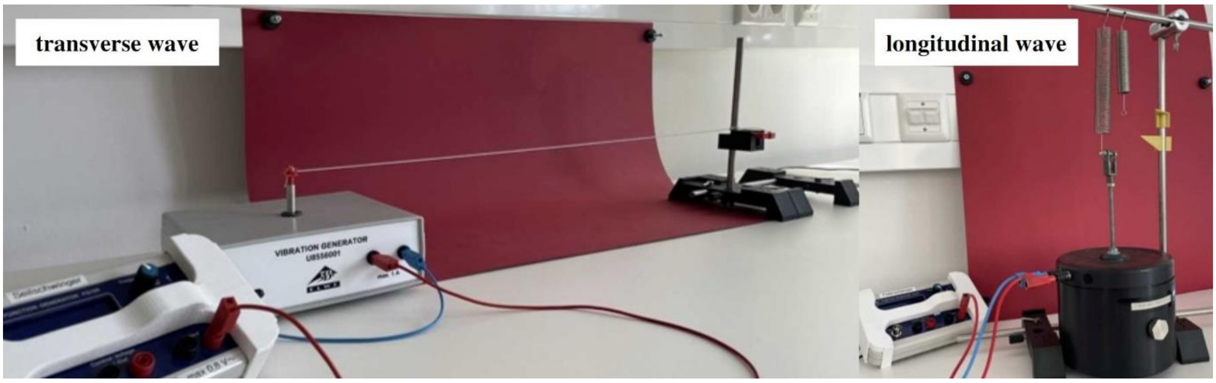

Figure 3. Experimental set-ups

For the generation of standing transversal waves, a bungee cord is firmly clamped between a holder and a shaker. The shaker excites the cord by sinusoidal movements of a set frequency, which is generated and adjusted with the help of a function generator. In total, the first five harmonics have to be located and their values documented. The frequency is plotted as a function of the number of antinodes. Also, the propagation speed is plotted versus the frequency. By studying the plotted diagrams, students should discover a linear relationship between the frequency and the number of antinodes. They should also see that the corresponding wavelengths becomes smaller with increasing frequency. In this manner, the propagation speed remains constant with frequency changes. An identical procedure is followed in the second experiment involving longitudinal waves using a coil spring.

4.3 AR experience concept development

At Ostfalia, a standardised flow chart developed by J. Chlebusch was worked through before generating any AR experiences. With this flow chart, among other things, the focus and the type of experience can be determined (Chlebusch et al., 2020). In addition to the basic formulation of the teaching objective, the teaching objective must be classified in context of Bloom's learning objective taxonomy before the questionnaires are carried out. This is divided into the six levels of complexity 1: Knowledge, 2: Understanding, 3: Application, 4: Analysis, 5: Synthesis and 6: Evaluation (Bloom, 1956). The AR experience to be created should cover the first four levels. In addition to the knowledge transfer, the application of the knowledge in the comprehension questions and the execution of the experiment, the students must finally be able to analyze their results and document them in the experimental report. After going through the flow chart, the mixed form turned out to be the best way of teaching. Three-dimensional content, animation and 3D/2D interaction are to be incorporated. The focus is defined as mediation, lack of time and motivation with decreasing priority. To achieve the goals described in Section 3, while considering the insights gained from the flowchart and, not allowing the information density per AR experience to become too great, the AR experience is divided into three parts. The teaching content is, thus, distributed over three experience slides, each with a predefined ThingMark and the corresponding two-dimensional real information. The first AR experience is intended to convey the physical basics and the second to show the experimental set-ups with their special features. These two experiences serve to prepare for the experiment and are to be experienced by the students before the laboratory appointment. The third AR experience provides support for the execution of the experiment. The lab participants start the AR experience in the lab at the beginning of the experiment execution. The

https://doi.org/10.1017/pds.2023.324 Published online by Cambridge University Press

division is illustrated in Figure 4. A set of slides is created for the integration of the AR experiences into the laboratory documents. This consists of six slides, composed of a cover sheet, AR experience application instructions, a questionnaire and the three experience slides.

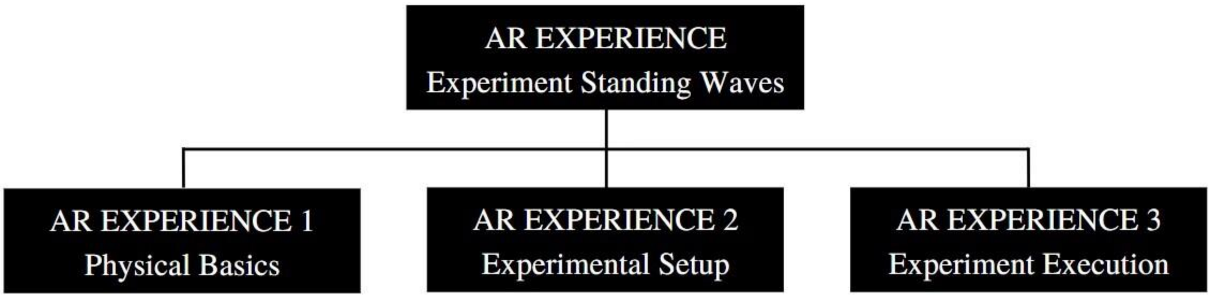

Figure 4. AR experience concept

4.4 Creation of the AR experience

Based on the concept developed in Section 4.3, the three-part AR experience is then created with the help of the PTC tool chain (Creo Parametric, Creo Illustrate and Vuforia Studio). In order not to exceed the scope of this paper, the work for the second AR experience on the structure and function of standing transversal waves is presented below as a minimized example.

The three-dimensional components required for the AR experiences are modelled in the Creo Parametric software and partly assembled. Furthermore, animation modules for the wave movements are already prepared in this program, which can then be further used in Creo Illustrate. The waves in the AR experiences are to be represented by coupled mass points. This makes it easier to understand how waves work and makes it clear that they do not transport matter, but only energy and impulses.

AR experience 2 is broken down into the two experiments for the standing transverse and longitudinal waves. The user also has three interaction options for each experimental setup. Displaying the labelling of the components, starting the wave animation to recognize the function, and displaying special features that need to be paid particular attention to during execution and evaluation. Within Creo Parametric, all the necessary components, labels and markings are modelled realistically and composed into an assembly. This leads directly to overlapping of components and thus to a lack of clarity. The differentiation into the individual interaction options, however, first takes place in the subsequent step in Creo Illustrate. Finally, a function integrated in Creo Parametric animates the mass points in a wave motion and saves them as an animation block for further use. Figure 5 shows the assembled module for the experimental setup of the standing transversal waves.

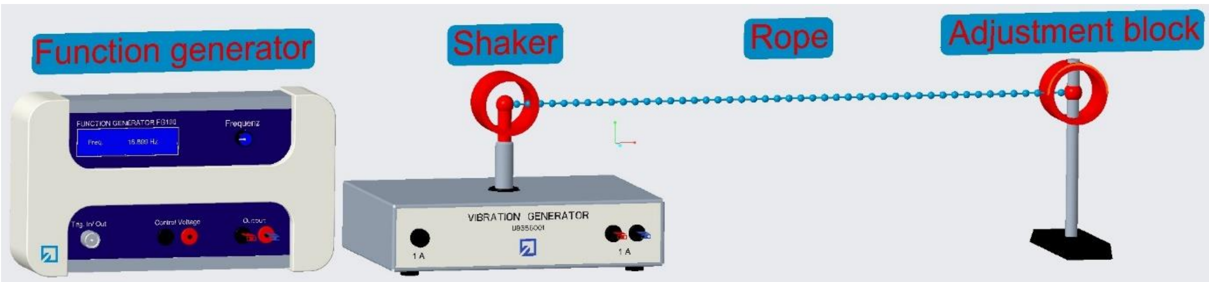

Figure 5. AR experience 2.1 - Creo Parametric

In the subsequent Creo Illustrate software, the animations of the virtual three-dimensional tree groups for the AR experiences are created. Since the respective undulations have already been animated in Creo Parametric, the focus of the work in Creo Illustrate is on fading in and out components that are not needed and completing the prepared animations with, for example, fade-ins and fade-outs of the entire assembly located at the beginning and the end. This work allows clear interaction possibilities within the AR experiences.

The final conversion of the prepared files into the AR experiences takes place in the Vuforia Studio software. Here, both the components and groups are positioned in three-dimensional space, in relation to the ThingMark on the experience slide, and the two-dimensional user interface is created and deposited with interaction options for the user. In order to ensure clarity within the AR experiences

https://doi.org/10.1017/pds.2023.324 Published online by Cambridge University Press

and not to let the information density become too large, several levels with different interaction possibilities are created. Below that is also a level for student knowledge retrieval. Finally, so that the lab management can read out the user's input as needed, the experiences are linked to a database (PTC's ThingWorx IoT system). Figure 6 shows the AR experience for building the standing transverse waves in the application. In this case, the animation was started to see how the setup works. In addition, the real image of the experimental setup is virtually marked on the experience slide to achieve an even stronger learning effect.

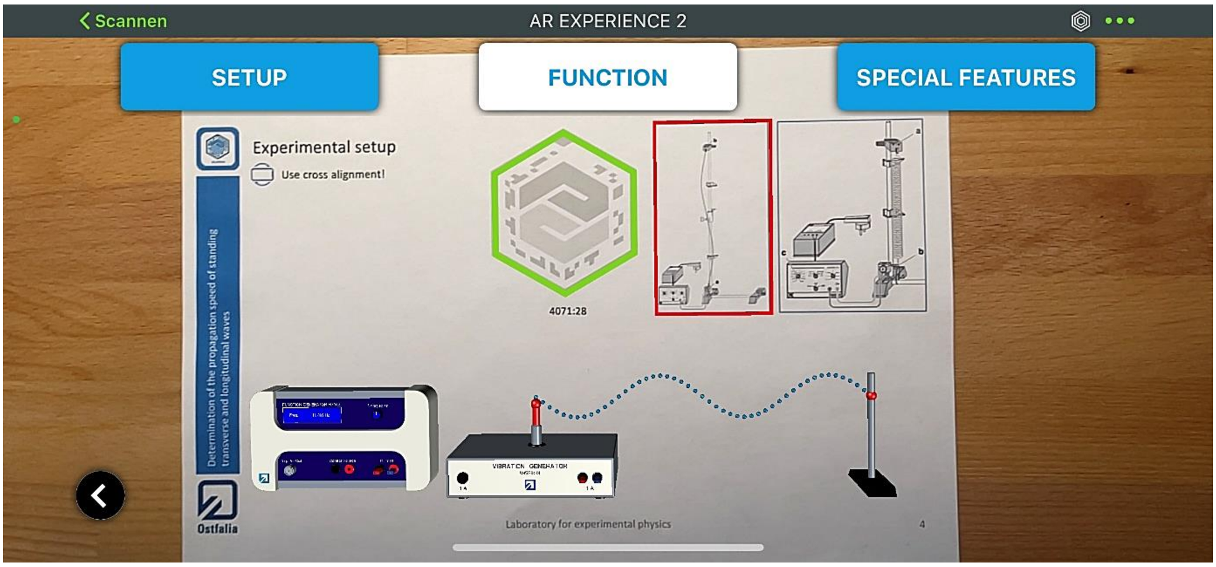

Figure 6. AR experience 2.1 - transversal waves - function animation

5 EVALUATION OF THE EFFECTIVENESS

An evaluation was conducted with students who participated in the experimental physics lab to determine the effectiveness of the created AR experience. It should be noted that the evaluation was designed for the AR experiences in their entirety and, therefore, no distinction was made between preparation and implementation experiences. At the beginning of the semester, participating students were randomly divided into two groups. The control group (12 students) performed the experiment using only the pre-existing two-dimensional laboratory documentation. The students in the test group (16 students) additionally received the AR experiences.

After the laboratory tasks were completed, a Confidence-Based Assessment according to Novacek was conducted (Novacek, 2017). Both groups received a questionnaire (with the same questions), with which the technical/objective knowledge was tested. The questionnaire contained three questions each on the physical basics, the experimental set-up and the experimental procedure. Before answering each question, the participants were asked to estimate how confident they were in giving the answers.

The questionnaire of the test group was extended by questions that were used for a subjective evaluation of the use of AR. Included here are questions such as, "How would you rate your understanding of the topic before and after using AR-assisted preparation?" A 10-point scale was used to answer these questions.

To measure the influence of AR, the responses of the questionnaires are analysed. Subsequently, the effect size d of the VR is calculated according to Cohen.

- **What impact does AR have on the confidence-based grading?**

The analysis of the questionnaires shows that AR has a very slight negative effect on the confidence-based grading (Cohens $d \approx -0.15$).

- **Could the understanding be improved with the help of the AR?**

Contrary to the confidence-based grading, the correctness of the answers shows a very slightly positive effect (Cohens $d \approx 0.1$). Looking at question one, the result is plausible, because in confidence-based classification incorrect answers with high confidence have a stronger influence than correct answers with high confidence.

https://doi.org/10.1017/pds.2023.324 Published online by Cambridge University Press

- **Could the confidence of the students be improved with the help of the AR?**

The confidence in the given answers has deteriorated to a minor degree (Cohens d ≈ -0.3). With a view to the first two questions, this result is also plausible.

- **How do students feel about the impact of AR**

If the first six answers to the questions about the subjective perception of the test group (table 1) are examined, it shows that students felt that they had a better understanding of the content of the laboratory after working through the AR content (Cohens d ≈ 0.2). The results of question 7 show that the students enjoyed using the AR experiences (7.8/ 10). However, they are rather skeptical about using AR in other labs (6/10). One possible explanation for this is that while students enjoyed the AR experiences themselves, their novelty required additional time and effort, which students tend to view critically.

Table 1. Subjective perception

No.	Question	Ø Value
1	I already understood the physical principles for the experiment very well before applying the AR experiences	8.2
2	I already have a very good overview of the experimental setup with its special features before applying the AR experiences	8.3
3	I already felt well prepared and confident for the lab experiment before applying the AR experiences.	8.5
4	After using the AR experiences, I understood the physical principles for the experiment very well.	8.6
5	After using the AR experiences I fully surveyed and understood the experimental setup with its special features	8.7
6	After using the AR experiences I have felt well prepared and confident for the lab experiment	8.7
7	On a scale of 1-10, how much fun did you have using the AR?	7.8
8	On a scale of 1-10, how strongly would you support the use of AR in other labs?	6.0

6 SUMMARY AND OUTLOOK

In this work, how the use of AR-based teaching affects the results obtained in the Experimental Physics Laboratory: "Determination of the propagation velocity of standing transverse and longitudinal waves", was investigated. Confidence-Bases Assessment was used and the effect size of AR-assisted teaching was determined using Cohens approach.

It was found that the students felt better prepared for the lab because of the AR. This was also reflected in the accuracy of the test answers. On the other hand, the confidence of the test group in answering the question was lower than that of the control group. There was an inverse correlation between competence and self-perception. It should be noted, however, that the effect size is very small in all areas. Coupled with the comparatively small number of test subjects, the results obtained must be viewed critically.

One reason for the low effect size could be that the original competence level of the students is already very high, so that the positive effects that the authors expected from the use of AR could not take full effect. In addition, the complexity of the laboratory and the experimental setup is rather low (second semester). The authors assume that the effect of AR-supported teaching is much stronger with topics that are more complex. For this reason, the following points need to be investigated in future work:

- How does the effect strength develop with an increasing number of subjects?
- What is the impact of increasing the learning target level (cf. Bloom's learning objective taxonomy) on the effect size?
- What effect does the complexity of the subject matter have on the effect size?

In addition to these three points, the quality of the AR experiences used will improve in the future. For example, by being able to access the AR experiences via a head mounted display while conducting the lab.

https://doi.org/10.1017/pds.2023.324 Published online by Cambridge University Press

ACKNOWLEDGMENT

The authors express their gratitude to the Ministry of Science and Culture of the German state of Lower Saxony for funding the project "Innovation Plus - Expert Capture" (Inno+(2022/23), P008, 0608/68296). The authors are grateful to Mr. C. Oppermann and Mr. R. Sabath for supervision of the laboratory experiments as well as for their suggestions. Ms. J. Bode is thanked for her support during the evaluation.

REFERENCES

Alvarez-Marin, A., Velazquez-Iturbide, J. A. (2021), Augmented Reality and Engineering Education: A Systematic Review, In: IEEE Transactions on Learning Technologies. https://doi.org/10.1109/tlt.2022.3144356

Arnold, J., Sorge, S., Graulich, N., Kubsch, M. (2021), Lehrkräftebildung neu gedacht, Waxmann, Münster, pp. 237-242. https://doi.org/10.31244/9783830993490

Azuma, R. (1997), A Survey of Augmented Reality, In Presence: Teleoperators and Virtual Environments 6 (4), pp. 355-385. https://doi.org/10.1162/pres.1997.6.4.355

Bloom, B.S. (1956), Taxonomy of Educational Objectives, Handbook: The Cognitive Domain, David McKay, New York.

Chlebusch, J., Köhler, I., Stechert, C. (2020), Reasonable application of augmented reality in engineering education. In Presence: International Design Conference - Design 2020, pp. 1677-1686. https://dx.doi.org/10.1017/dsd.2020.62

Chu, Yih Bing (2022), A mobile augmented reality system to conduct electrical machines laboratory for undergraduate engineering students during the COVID pandemic. Educ Inf Technol 27, 8519–8532. https://doi.org/10.1007/s10639-022-10987-9

Doerner, R., Broll, W., Grimm, P., Jung, B. (2022), Virtual and Augmented Reality (VR/AR) – Foundations and Methods of Extended Realities (XR), Springer International Publishing. https://doi.org/10.1007/978-3-030-79062-2

Grothus, A., Thesing, T., Feldmann, C. (2021), Digitale Geschäftsmodell-Innovationen mit Augmented Reality und Virtual Reality, Springer Gabler, Heidelberg. https://doi.org/10.1007/978-3-662-63746-3

Hamadou, M., Jahn, D., Weidenhausen, J. (2004), ARVIKA – Augmented Reality for Development, Production and Service, i-com. https://doi.org/10.1524/icom.2002.1.2.004

Hanafi, A., Elaachak, L., Bouhorma, M. (2020), Augmented Reality Application in Laboratories and Learning Procedures, In Book: Innovations in Smart Cities Applications Edition 3, pp.157-167. https://doi.org/10.1007/978-3-030-37629-1_13

Hsu, C.-Y., Chen, M.-W., Wu, C.-C. (2015), Teaching high school computer science with videos of historical figures -An augmented reality approach, In: IEEE International Conference on Learning and Teaching in Computing and Engineering. https://doi.org/10.1109/latice.2015.30

Lang, M., Müller, M. (2020), Von Augmented Reality bis KI - Die wichtigsten IT-Themen, die Sie für Ihr Unternehmen kennen müssen, Hanser, München. https://doi.org/10.3139/9783446464353

Milgram, P., Takemura, H., Utsumi, A., Fumio, K. (1994), Augmented Reality: A class of displays on the reality-virtuality continuum, In: Presence: Telemanipulator and Telepresence Technologies, Vol. 2351. https://doi.org/10.1117/12.197321

Novacek, P. (2017), Exploration of a Confidence-Based Assessment Tool within an Aviation Training Program, In Presence: The Journal of Aviation/Aerospace Education and Research. https://doi.org/10.15394/jaaer.2017.1717

Orsolits, H., Lackner, M. (2020), Virtual Reality und Augmented Reality in der Digitalen Produktion, Springer Gabler, Heidelberg. https://doi.org/10.1007/978-3-658-29009-2

Tipler, P., Mosca, G. (2019), Physik - Für Studierende der Naturwissenschaften und Technik, Springer Spektrum, Berlin. https://doi.org/10.1007/978-3-662-58281-7

Yengui, M. H., Stechert, C. (2021), On the Activation of Students through Augmented Reality Experiences, In: Proceedings of the Design Society 1, Cambridge University Press, pp. 2307-2316. https://doi.org/10.1017/pds.2021.492

https://doi.org/10.1017/pds.2023.324 Published online by Cambridge University Press