Tangibility is Overrated: Comparing Learning Experiences of Physical Setups and their Virtual Equivalent in Augmented Reality

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ABSTRACT

Augmented Reality (AR) is gaining increasing importance in science, education, and entertainment. A fundamental characteristic of AR is blending the virtual and physical world into a coherent environment. In this paper, we examine the effect of substituting the physical components of lab experiments with tangible replicas and virtual representations. We conducted a user study with thirty participants who carried out the experiment in three different abstraction levels (original lab equipment, non-functional tangible props, virtual representation). We compared the users' performance regarding setup time, experienced workload, quality of measurements, and concept comprehension of the learning task. We found no effect on comprehension but significant differences in setup time and quality of measures. The results indicate that substitution reduces the experiment setup duration without affecting knowledge transfer. These results help to shape future AR learning environments, and we offer insights for creating complex mixed reality learning materials.

CCS CONCEPTS

• **Human-centered computing → Mixed / augmented reality**;
• **Applied computing → Interactive learning environments**.

KEYWORDS

Mixed Reality, Augmented Reality, Amplified Perception, Thermal Vision, Learning, Physical Substitution, Physics Lab Experiment

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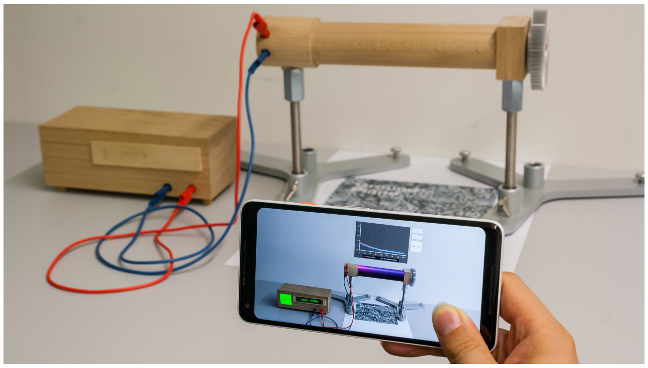

Figure 1: Thermal flux lab experiment with components substituted by non-functional replicas. Augmentations and simulation on smartphone enable functionality and interactivity of the experiment.

1 INTRODUCTION

Students of the academic disciplines of Science, Technology, Engineering, and Mathematics (STEM) struggle with the change from high school to universities. They are required to plan their class schedules and follow them consequently. Instructions are primarily through lecturing without close monitoring. The students' time management and their ability to study independently study are critical to success. This significant reorientation results in general high dropout rates. In the field of Physics, dropout rates of up to 40% in the first two semesters are common [8]. This circumstance urges continuous investigation, innovation, and evaluation of new educational concepts such as interactive engagement with peer instructions [6] or replacing lecturing sessions with student group problem-solving, to help improve retention rates.

Over the last decade, augmented reality (AR) and virtual reality (VR) hardware and software have matured and are now entering the consumer market. Cheaper hardware and low prototyping costs are further accelerating the developing processes. Recently we have

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seen more and more mixed reality applications targeting learning scenarios to stimulate self-paced learning, and for the first time, mixed reality applications are being explored beyond the lab. However, in the field of education and knowledge-sharing, analysis of mixed reality learning applications reveals that they have diverse effects on student performance [25]. In this work, we refer to mixed reality as a fusion of AR and VR in the Milgram reality-virtuality continuum [21].

Mixed reality applications offer a potential solution to one of the fundamental problems many students in the disciplines of STEM and in particular the field of Physics face: abstract concepts and laws based on quantities that are not directly visible to the human eye. Electricity, for example, is such a concept. We can measure resistance, current, and voltage with a multimeter but cannot visually perceive these quantities directly. Beheshti et al. [2] developed a tablet-based AR application and visualized electrons flowing through a circuit to foster a better understanding of electrical circuits.

In this work, we present our development of an AR application enabling students to observe the heat flux through a metallic rod. The rod is heated on one side with a cartridge heater while cooled on the other by a standard CPU fan to generate a temperature gradient. To supervise the physical effect taking place, students use a handheld mobile device to visually perceive the temperature using a false-color representation overlaying the metallic rod. Additionally, a graph, depicted in Figure 1, is floating above the experiment setup and visualizing real-time temperature values captured by an infrared camera.

Based on this experiment, we developed two abstraction levels by substituting the physical functional pieces of the experiment. First, we replaced them by non-functional replicas and later by entirely virtual representations. The non-functional replicas maintained a similar setup procedure and presupposed interaction with the experiment components. The functionality is reinstated through simulation, while augmentation enables interactivity. The solely virtual abstraction of the experiment does not include any physical items. Hence, it allows students to experience the experiment almost everywhere. We conducted a user-study to answer our research question on the effect of substitution and virtualization of lab experiments. We invited 30 participants investigating the effects on task completion time to set up the lab experiment, perceived workload, complexity, and quality of measurements.

We contribute an architecture description of an AR application to enhance human perception in a physics class. We further contribute with the findings of our user-study that indicate significant faster setup times through the substitution of physical items while improving the overall quality of experimental measurements. With our apparatus, we regulate the invested time and enable students reviewing experiments with minimal effort.

2 BACKGROUND

With the proliferation of new AR devices like the Microsoft HoloLens and smartphones supporting the fast development of AR applications through powerful libraries [15, 20], AR has gained much research attention in recent years. In this section, we will give a brief overview of the concept of augmented and simulation-based learning environments.

AR learning environments provide a unique set of features and affordances that are often adopted from other domains as ubiquitous and mobile computing [33]. New learning opportunities include individual learning pace to alleviate the overall workload of supervisors and students [19]. These AR systems offer new possibilities to manipulate and engage directly with the interactive content presented in the real environment [1] and do not rely on external supervision.

Simulations enable further abstraction from the real learning material. Students that used computer-supported experiences and learned with AR showed a higher performance in conceptual questions and developed a greater facility at manipulating real objects and understanding physical phenomena. Computers can be used to further promote student learning and skill development in reasoning and manipulating [10]. Even on a higher level of abstraction, AR has been shown to support teaching elementary school students mathematical concepts, such as fraction [24].

In traditional teaching scenarios, teachers usually educate using analog media, such as whiteboards, and some handheld teaching aids. New media, and particularly digital media, is used only occasionally. In such cases, these teaching methods can provide students with specific object observation experiences, such as interactive learning material. These teaching methods are centered on the teacher and allow a structured and guided learning experience. However, students may lack the chance to develop learning autonomy. DiSessa [7] argues that computers can be fundamental for a new kind of literacy that can revolutionize how students think. Further, he critically discusses how new immersive technologies can be integrated into learning to make learning material exciting and intellectually generative. Without a clear focus, learning material may not foster knowledge.

Learning also includes collaboration and dialogue with peers, but integrating these characteristics into an AR environment can be particularly challenging. Having a heterogeneous group with non-immersed collaborators adds an additional level of complexity [13]. Researchers have found that concepts like face-to-face communication [3], shared spaces and objects, as well as new forms of user interaction, can enhance collaboration, and several AR and VR experiences have been developed to investigate how to solve tasks as a group collaboratively [22].

With the rapid development of sensor-equipped smartphones, they have also become a helpful utility in physics classes. The built-in accelerometer has been used to teach pendulum phenomena [31], and the camera helped students to slow down or speed up [26] physical phenomena. With the introduction of mixed reality support for smartphones, many research projects implemented AR to improve and stimulate learning. As already pointed out, Beheshti et al [2] visualized the electrons within the wires of a circuit to convey basic concepts of current and resistance in electric circuits. Using AR glasses, Bodensiek and Sonntag [4] augmented a fine beam tube allowing students to get immediate feedback on experimental actions. With a thermal flux experiment, very similar to our development, Strzys et al. [28, 29] visualize the invisible and amplifies human perception. Students were enabled to evaluate and directly examine the physical process itself using smart glasses.

There is still an open discussion to what extent AR and VR environments can support learning. An extensive analysis of 87 research articles showed a small adverse effect to a significant effect [25]. Radu [23] analyzed 26 AR publications in-depth and found that AR provides opportunities for educational use of 3D spatial and kinesthetic content. However, AR may be less suitable for textual content or 2D simulations. Besides, AR introduces technological, managerial, and cognitive challenges to technical assistants', teachers, and learners [9, 17] Learning is a complex concept that goes beyond simple knowledge processing and acquisition [14]. Within learning theory, active participation, learning sequences that comprise several activities are considered as crucial [27, 32].

With our work, we further investigate how learning can be supported through AR, simulation, and virtualization. We specifically focus on the effect of substitution and virtualizations of functional components of real physical laboratory experiments. We research if students in the field of Physics or other interested parties could benefit from augmented virtualized lab experiments and foster a better understanding of the underlying concepts.

3 DESIGN OF THE THERMAL EXPERIMENT

During the development process we followed constructivist learning theory that emphasizes active involvement of students in constructing knowledge. A additional design element we considered is mobile learning [27] to elate students to use the application beyond the lab course. We tailored our augmented reality application to teach heat conduction in metals for an introductory laboratory course in thermodynamics. Previously, students had been required to take snapshots with a handheld thermal camera to acquire data and do an offline analysis. With our application, students get real-time feedback and enhanced data visualization of the experiment and can observe the thermal flux.

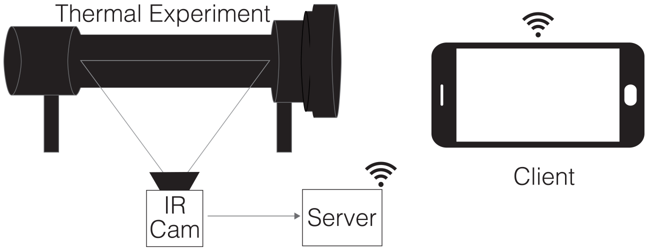

Figure 2: The architecture comprises the thermal lab experiment, an infrared camera, and a server, streaming real-time experiment data to the smartphone that renders the in-situ overlay.

3.1 System Architecture

Our system is based on prior developments [16, 18] and comprises the thermal experiment itself, an infrared camera attached to a server and an augmented reality display acting as a client. Our simple server-client architecture supports multiple users to enable collaborative experiment execution. An overview of all components is depicted in Figure 2.

The thermal experiment itself consists of several metallic rods made of aluminum, copper, or brass. A power adapter supplying 12 volts is used to control the temperature of one end of the metallic rod. Further, there are insulated rods to generate different thermal flux properties.

The infrared camera is centered in front of the metallic rod to capture real-time temperature values. These are forwarded to the server for further processing. The infrared camera is connected via USB to a computer running a server application and image processing pipeline. The captured infrared video feed is analyzed and based on the temperature signature, the metallic rod is registered within the data. The sampled temperature data is recorded and sent wirelessly via a simple communication protocol to the client on request.

3.2 AR Application

The augmented reality display renders the false-color representation on-top of the metallic rod as well as plotting the floating graph above the experiment setup representing the real-time data. The AR display needs to register the setup in space to correctly place all augmentations on top of the experiment. In our prototype, we specifically utilize a smartphone that supports advanced AR capabilities. To register the experiment in space, we use the Vuforia framework[1], the back-facing camera of the smartphone and printed a marker to identify the experiment's location in space. Finally, the augmented reality display gives in-situ hints and additional information to guide the students through the experiment.

4 METHOD

To evaluate the effect of the different levels of substitution and virtualization of the thermal experiment, we designed a controlled laboratory experiment. The independent variable (IV) APPARATUS consisted of three levels of abstraction: *real*, *replica*, and *virtual*. We ensured that no differences in data visualization biases the results of the study. Since none of the participants should conduct the physical experiment twice, APPARATUS was used as the between-subject variable.

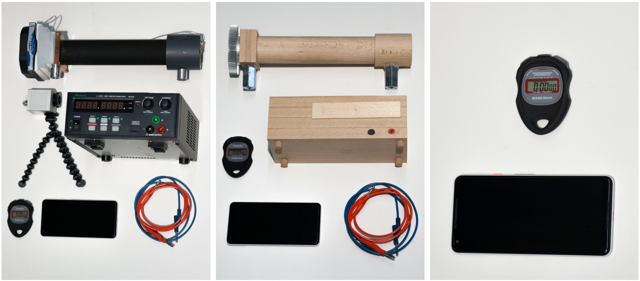

Figure 3: Entities for experimental assembly for all three conditions. (Left) *real*: Power supply, metal probe, thermal camera, wires, smartphone and stopwatch. (Center) *replica*: wooden power supply replica, wooden probe replica, wires, smartphone and stopwatch. (Right) *virtual*: smartphone and stopwatch.

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[1] https://library.vuforia.com/

4.1 Conditions

Each participant was invited to conduct the thermal experiment in one of the three conditions described below. An overview of all three set-ups, including the AR overlays, is illustrated in Figure 4.

4.1.1 Condition 1: Real Setup. The *real* setup condition comprised the original thermal flux experiment that is currently conducted by students in the Physics lab. Students could observe the experiment through the augmented reality display and get live data captured from the thermal camera. In the *real* setup condition, participants were asked to execute the full experimental set up, which includes probe set up, camera calibration, wiring and operating the power supply. All necessary hardware components are depicted in Figure 3. The setup including the AR overlay is depicted in Figure 4.

4.1.2 Condition 2: Replica Setup. In the second condition, we replaced the original brass probe with a wooden replica of the same size and shape. Thus, the replica could be mounted on the same tripods. The power supply was also replaced by a wooden replica including wooden elements indicating a display and plugs. Both the probe and the power supply replica had color-coded drilled holes to allow to plug in regular laboratory-style banana plug cables. The smartphone application was extended by the ability to augment the power supply and visualize a virtual power button and display to present the current values for electric potential and electric current. In contrast to the *real* setup, in this condition, participants were not required to set up and calibrate the camera. Instead, previously recorded data was streamed from the server and visualized respectively to the status of the power supply.

4.1.3 Condition 3: Virtual Setup. In the *virtual* setup condition, no physical components except of the smartphone and stopwatch were involved. The experimental probe, thermal camera, power supply, and wires were replaced by their virtual counterparts and rendered within the AR display. Again, the power supply had a virtual power switch to turn on the supply and start the experiment. Thermal data was provided from the previously recorded data set and was overlaid in exactly the same way as in the other conditions.

4.2 Apparatus

Our server application ran on a RasperyPi 3. This application provides a user interface and live stream for the thermal camera for calibration for the *real* condition as well as data streaming of recorded or real-time thermal data. In the *real* condition, we utilized an Optris PiConnect 160 infrared camera with an optical resolution of 160 x 120 pixels at 120 Hz and a spectral range of 7.5 to 13 μm. We used the Google Pixel XL smartphone with 64 GB as AR display running our previously outlined Unity application.

4.3 Task

In this study, the participants had to conduct a simple thermal flux experiment that is widely used in laboratory classes. They were asked to set up the thermal flux experiment according to the printed manual. Depending on the APPARATUS, this task involved different steps. For the *real* or *replica* condition, the metallic rod sample, camera, and power supply or the wooden replicas needed to be placed in the experiment area; and the power supply (real or wooden) needed to be connected to the heating and cooling element. For the *real* setup, the thermal camera needed to be aligned and calibrated. Since the *replica* and *virtual* condition do not rely on live data, the camera was not involved in this setups. For the *virtual* setup, only the smartphone was used, and no other components had to be set up. After successfully setting up the experiment, participants had to switch the power supply and start the stopwatch. During the heating process, the participants' task was to record the minimal and maximal temperature at intervals of 2 minutes for 10 minutes.

4.4 Procedure

After welcoming the participants, we asked them to sign the consent form and take a seat next to the dedicated experimental setup area. We gave a brief introduction to the thermal flux experiment and explained the study. We assigned each participant to one of the conditions and showed them to the appropriate table next to the setup area that contained all the components. The different components for each condition are shown in Figure 3. We explained how to start and use the AR application and handed the participants the assembly instruction and task description. They set up and conducted their experiment, observing the thermal flux, and recording the temperature values. Throughout the study, we gave advice on request and manually logged time and errors made. After finishing the experiment and answering the knowledge questions, the participants filled out the NASA-Task Load Index (TLX) [12] and System Usability Scale (SUS) questionnaire [5]. In the last step, we collected demographic data, and the participants filled out the compensation form. Including debriefing, the participants completed the study in 25 to 40 minutes.

4.5 Participants

We recruited 30 participants (8 female, 22 male) aged from 18 to 55 years ($M = 28,45y, SD = 7,77$) via our university mailing list and social media. All were undergraduate students with mostly (11) technical background. All participants had normal or corrected to normal vision, and 23 of them had previously experienced AR. Participants received a small gratuity and either course credits or 5 EUR as compensation for their participation.

4.6 Measures

Since we wanted to evaluate the extent to which augmentation aids learning, we focused in assessing the effort required to prepare and perform the thermal flux experiment, as well as the gain of knowledge. To gather quantitative data about these aspects, we measured the setup time, perceived task load, system usability, and the quality of acquired thermal values. The setup time was measured from handing over the printed manual to the participant to physically or virtually switching the power supply to start the experiment and heat up the probe. We assessed SUS [5] and TLX [12] through questionnaires presented in a web browser. These metrics reflect respectively the cognitive and physical load associated with the task and to which degree was each condition easy and convenient to use.

We evaluated the understanding of the experiment itself through free text questions, which we ranked by quality and completeness.

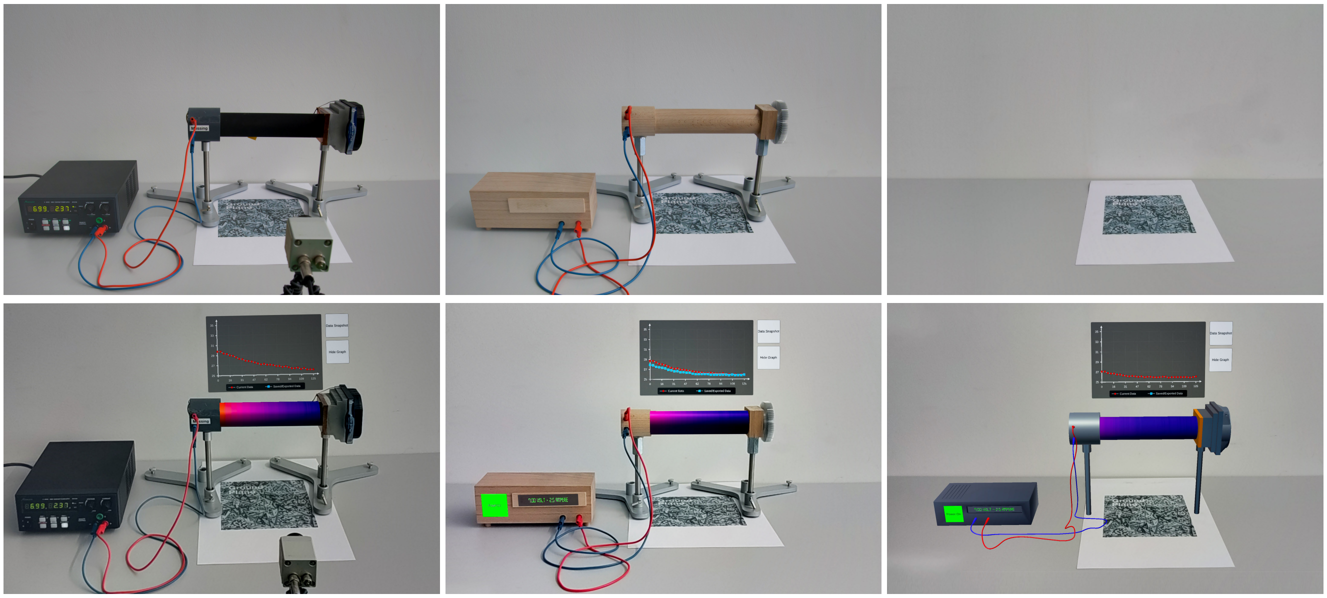

Figure 4: Three experiment condition setups from left to right: *real*, *replica*, and *virtual*. Each without (top) and with (bottom) augmentation of the experimental area. Augmented images are screen captures done during the experiment.

Questions were adapted from the Heat and Temperature Conceptual Evaluation (HTCE) [30] questionnaire and targeted on temporal and spatial properties of the probe. We also manually recorded the necessary help or errors during the setup and execution of the experiment.

5 RESULTS

We conducted multiple one-way independent-measure analysis of variance (ANOVA) with the between-subjects variable Apparatus. The homogeneity of variances was tested using Levene's test. All significance levels are at $\alpha = .05$. The results are visualized in Figure 5.

5.1 Task Load Index (RAW NASA-TLX)

To assess the users' perceived task load while conducting the thermal flux experiment, we used the TLX score of the NASA-TLX questionnaire. All recorded NASA-TLX scores are very similar with *real* ($M = 29.80, SD = 14.28$), *replica* ($M = 29.80, SD = 12.73$) and *virtual* condition ($M = 30.20, SD = 15.53$). Hence, a one-way independent-measures ANOVA could not reveal a significant effect of Apparatus on one of the three conditions ($p > .05$).

5.2 System Usability Scale

Considering the SUS, representing the subjective usability of the system, the *real* setup condition led to a higher subjective usability ($M = 89.25, SD = 6.877$) compared to the *replica* ($M = 86.75, SD = 6.877$) and *virtual* ($M = 84.00, SD = 8.991$) condition. A one-way independent-measures ANOVA could not reveal a significant difference between the three conditions ($p > .05$). We conclude that for this experiment the Apparatus does not significantly effect the effort required to prepare and perform the experiment.

5.3 Setup time

Setting up and calibrating all components of a physical experiment consumes time. After handing out the experiment instructions to the participant, we recorded the time (in sec.) it took them to prepare and initiate the thermal flux experiment. The *virtual* setup condition led to the lowest setup time ($M = 71.40\,sec, SD = 24.99$) followed by the *replica* ($M = 152.10\,sec, SD = 61.25$) and *real* ($M = 335.20\,sec, SD = 89.10$) A one-way independent-measures ANOVA revealed a significant difference between the conditions $F(2, 27) = 44.51, p < .001, \eta^2 = .767$.

Post hoc analysis was performed using Bonferroni corrected pairwise t-tests to determine statistically significant differences between all conditions. Post hoc comparisons of the average set up time until experiment start revealed significant differences between all three conditions. (all with $p < .05$). Further, Cohen's effect size value (all $d > 1.7$) suggested a large practical significance. We conclude, that reducing the number of setup steps and tangible components improves the required time.

5.4 Acquiring Thermal Values

The absolute difference in Celsius from the measured means was taken as an index of quality for the measurement. To determine if there was a significant difference between the absolute difference of the three conditions, we performed a one-way independent measure ANOVA. Results show a significant main effect of Apparatus on the quality of measurement ($F(2, 291) = 55.29, p < .001, \eta^2 = .275$)

Bonferroni corrected pairwise comparisons revealed a significant difference. The *virtual* ($M = .144, SD = .143$) condition has higher measure of quality than *replica* ($M = .357, SD = .447$), ($p < .001$) and *real* ($M = .767, SD = .570$), ($p < .001$). Further, the *replica* setup leads to higher measure quality compared to *real* ($p < .001$). We

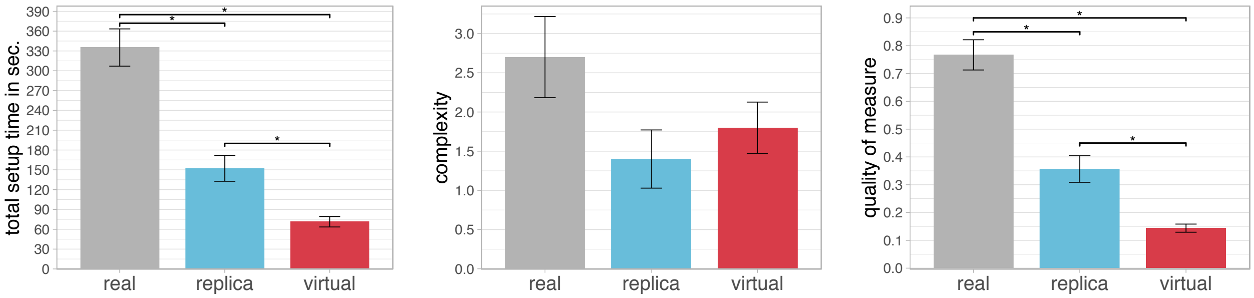

Figure 5: Mean values for set up time in seconds, complexity as sum of errors and given assistance and quality of measures for each condition. Error bars show standard error of the mean (SE). Asterisk indicate statistically significant differences between conditions.

conclude, that participants recorded more accurate data using our *virtual* Apparatus due to the simplified setup routine.

5.5 Knowledge Transfer & Complexity

Questions were ranked from wrong (1), neutral (2) to correct (3) allowing a total score of nine points. *Replica* led to the best results ($M = 5.6, SD = 1.71$) followed by *virtual* ($M = 5.5, SD = 2.21$) and *real* ($M = 4.6, SD = 2.63$). A one-way independent-measures ANOVA revealed no significant difference between the conditions (all $p > .05$). We summed up all errors and required assistance during the implementation of the experiment as a measurement of complexity. In the *replica* condition, participants required least assistance ($M = 1.4, SD = 1.17$) followed by *virtual* ($M = 1.8, SD = 1.03$) and *real* ($M = 2.7, SD = 1.63$). Thus statistical analysis of the results revealed no significant difference between the conditions, participants in particular struggled during calibration and setting up the thermal camera and required assistance on the AR application start.

6 DISCUSSION

The proposed system enables students to perceive physical phenomena in a novel and more relatable way. Our results show that the setup time using the abstracted more virtual versions of the experiment was significantly reduced compared to the original lab experiment. Spending less time on setup and calibration allows investing more time in complex tasks like knowledge transfer or understanding the experiments and underlying concepts. It remains an open question if and to what extent experiment preparation contributes to the knowledge fostering process. However, several works evaluating augmented learning environments show that students perform significantly better when relying on AR and simulations [2, 10, 11].

As we found no effect between the conditions for TLX and SUS, we cannot confirm that reducing functionality by substituting real objects with their virtual equivalent reduces workload or increases usability on a large scale. However, the data indicate lower complexity for the abstracted experimental setups. Therefore, we expect higher possibilities to run lab experiments at home without external guidance correctly.

Our results imply a significantly higher quality of measures for the more virtual experiments. We are confident that higher errors are a combination of camera orientation, calibration, distraction, and error in measurement. For an adequate offline analysis of the experiment, exact measurements are crucial to derive correct conclusions. Hence, data acquisition based on simulated data could reduce students' frustration caused by noisy data recordings.

Setting the invested time, quality of measurement, knowledge transfer, and complexity, in contrast, our results suggest that it is possible to run augmented experiments of abstract concepts with reduced complexity. We recommend lower complexity, in particular, if no technical assistant is available to assist students.

Based on our findings, we recommend conducting the real experiment once and repeatedly carrying out slightly adapted variants with nonfunctional augmented replicas. Thereby, future implementations of augmented experiments can support students to foster learning. We assume students will further benefit from the opportunity to retake an experiment based on simulated or recorded data.

7 LIMITATIONS AND FUTURE WORK

Participants were mostly students with a technical background; however, we did not invite students from the field of Physics to the user-study. Consequently, the findings may not fully apply to all teaching scenarios. Nevertheless, considering this more heterogeneous groups we used, our findings are very applicable for less specialized learning environments like museums and or secondary school.

Measuring knowledge transfer is challenging, and we only analyzed at the first glance to investigate overall knowledge gain. In particular, we did not investigate the long-term effects of substitution and augmentation. We believe that a long-term study will provide more insights into the effects that augmentation and substitution can produce on learning.

We envision that future iterations of this contribution might consider different experiments on various physical effects, covering diverse fields of Physics. We argue that substituting experiments with carefully considered mixed reality environments can outperform real-world experiments. Students can particularly benefit from simulations and a more extensive variety of experiments since virtual adaptations of the experiments in size, shape, material, or the like will be inexpensive. Augmented and virtualized experiments could also be very beneficial for remote teaching or for students with impairments. Based on their skill additional information could be displayed or read out.

8 CONCLUSION

Many students struggle with understanding abstract physical concepts since they rely on non-visible quantities. In traditional experiments, students often do not get real-time data visualization. In this work, we presented our prototype of an augmented experiment visualizing thermal flux in situ. We developed three variations of this experiment substituting the real pieces with non-functional replicas and virtual representations. In a user-study with 30 participants, we investigated the effect of substitution and augmentation. In this specific scenario, all three conditions led to a similar ability of the students to learn the topic and transfer the knowledge. Our data reveals that there is no significant advantage for having a tangible setup (real or wooden replica) with regard to comprehension and knowledge transfer. Similarly, our experiment also shows that the task load for all three variants is similar as well as the required support. However, there are significant differences in the time that is required to carry out the task. The setup time with physical components is significantly higher. With regard to the quality, basically the measurements taken by the participants, the virtual version shows a significantly lower deviation of the measured values from the real values. We believe that this increase in quality is due to the lower complexity of the setup and simulation of data. Overall, our results provide evidence for the explored experiment, that there is no educational value of the tangible and physical setup.

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