

Article

Digital Experiments in Higher Education—A “How to” and “How It Went” for an Interactive Experiment Lecture on Dental Materials

Benjamin Kruppke 

Max Bergmann Center of Biomaterials, Institute of Materials Science, Technische Universität Dresden, 01069 Dresden, Germany; Benjamin.Kruppke@tu-dresden.de

Abstract: A digital lecture with motivating experiments—how can this be done in practice? This question shall be answered in the context of a case report from the field of material science. A digital experimental lecture as a substitute for a lecture with student experiments was evaluated by students to provide information on whether an adequate substitute for experiments in the digital teaching context is possible. This paper addresses the question of how to transfer a demonstrative experimental lecture to the digital space on two levels: (a) the procedure of an experimental lecture in the digital space with a focus on implementation, student activation, and audience response. A self-reflective assessment by the lecturer/author and an evaluation by the participating students was performed to judge the suitability of the digital experimental lecture in terms of students’ motivation. (b) Subject-specific experiments from the field of dental materials and their transfer from “students do it themselves” to a series of demonstration experiments. The detailed explanations of the procedure and the observed results shall serve as a basis for adaptation for other experiments or lectures. In conclusion, methods and tools (audience response systems such as joined blackboards, chat, and voting) suitable to activate students in partaking in the lecture by suggesting experimental parameters or speculating on the outcome of experiments are presented. The evaluation showed that with the help of these systems a demonstrative experimental lecture in the digital space can still be perceived as adequate experimentation if a certain student influence and animating approach to the audience is integrated, which might result in the students’ conclusion of, “It felt like you were “live” on site.”.

Keywords: synchronal; student’s activation; high education teaching; university; Christmas lecture; carries; tooth dissolution; corrosion; materials science



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1. Introduction

The transfer of courses into the digital space by means of asynchronous or synchronous lectures and seminars leads to a strong restriction regarding immediate feedback and communication between students and teachers [1,2]. In addition to this limitation, another form of teaching becomes difficult to implement in the digital space, and that is practical/lab courses with educational experiments [3]. This paper addresses the challenge of conducting a teaching course in the digital space with motivating (hands-on) experiments and achieving student participation by means of audience response systems. The basic question is whether students are able to overlook the demonstrative aspect and perceive the course as a practical experience owing to activating elements (with expectation queries, suggestions for the selection of parameters and the execution of experiments, and peer evaluation) or whether they perceive the video transmission as a distancing barrier.

The initial motivation for the paper was to establish an experimental lecture with interactive elements in the digital space. Digital experiments shall be understood in this context as demonstrated experiments, i.e., performed by an operator, which are (only) accessible to the students viewing it by means of digital broadcast technology. In the specific context of

this publication, the term also includes the direct feedback opportunity for students during the synchronous experiment broadcasting through audience response elements.

In order to illustrate the implementation of digital experiments, an extensive collection of experiments from the field of materials science, in particular dental materials, was integrated into the experimental lecture. This second subject-specific part, which is also a component of this publication, concentrates on suitable experiments, which should be easy to implement and, after adaptation, transferable to other subject areas. In addition, the results and discussion suggestions should stimulate imitation and further development of the experiments. Of course, the significance for dentistry and dental material application or examination is also important.

In general, it should be noted that in the course of the digitization of higher education, many lecture forms have been tested and discussed in the literature, with a focus on didactic methods (e.g., polls, group work, teacherbots, artcasting, inverted/flipped classrooms, tweeting book projects, etc.) [4–6], technical tools (e.g., Zoom, Prezi, pre-recorded video lectures, etc.) [7–9], and social-economic impact (neoliberal transformation of education) [10]. However, the transfer of experiments into the digital space seems to be underrepresented, which is probably due to the fact that the original self-learning effect is missing and there is a high risk for demonstration only. In order to avoid this, the activation of students before and after the experiments with expectation queries and explanatory discussions is described in detail in this paper.

Audience response systems are an important approach to motivate and engage students when used correctly [11]. This was found by K. C. Good, who additionally stated that the quantity and quality of different question structures by audience response systems (clickers) influenced student perceptions and supported student learning in presence lectures and might be transferred to digital lectures with ease. Furthermore, her review on the students' perspective supports the association of audience response systems with terms like "enjoyable" and "fun," with reduced desire to skip class, and the students desired to remain anonymous [11]. A more systematic model of the student experiences of using audience response systems was given by Wood and Shirazi, pointing out that students connect the themes of engagement, interaction, anonymity, questioning and discussion, instant feedback and student learning, and technological benefits and limitations to those systems. In order to not carry out the audience response methods for their own sake, K.C. Good as well as Kay and LaSage emphasized the importance of explaining the pedagogical goal [11,12]. They described that students generally respond positively to audience response systems, but often express the fear of feeling uncomfortable when responding incorrectly, particularly when a majority of the class responds correctly. This aspect should be taken into account in the use of audience response systems by not focusing the questions in a public (albeit anonymous) knowledge check, but rather on the subject-specific co-creativity of the students and a co-creation of a bigger picture out of individual contributions.

The challenge, as such, is to set an incentive for a particular lecture that goes beyond module grades and assessments. In this particular case, it is the field of dental materials, which represent an economically significant but nevertheless very special subgroup in the field of biomaterials, which in turn are located in the far more comprehensive part of materials science. One might think that the fact that we all come into contact with dentists and the materials they use sooner or later should already generate intrinsic motivation. However, the existing threshold between dentist and patient, which is reflected, e.g., in the language (characterized by Latin technical terms as well as uncommon orientation terms), seems problematic here. Furthermore, it must be urgently emphasized that the subject matter of dental materials is very different from the actual medical processes and background. Thus, starting from the natural model, i.e., the tooth and periodontium, the predominantly artificial materials for the treatment of dental defects are discussed on the basis of their chemical and physical properties. Thus, material selection, mechanical characteristics, testing of biocompatibility with the various tissues of the mouth, corrosion

effects and types, and degradation and wear processes are in the focus of this subject area and only indirectly provide a reference to specific treatment procedures.

This dichotomy between the expectations of students from the field of materials science and the actual teaching content gave rise to the idea of illustrating materials science issues through experiments. Unfortunately, it is an approach that cannot be transferred into the digital teaching environment with ease. This leads to the question of how an experimental lecture can be structured and which methods and tools it needs in order to give students the feeling of being able to participate in the execution of the lecture—in other words, the question of how to remove the demonstration barrier and how students accept the methods in the digital space. Therefore, first the question arose of how the experiments, which are time-consuming and may not be feasible in a face-to-face lecture format, can be prepared for a continuous broadcast in a synchronous digital lecture and be performed live by the lecturer without making significant cuts that would impair comprehensibility. In this context, the technical aspects of experiment broadcast, time slots for their introduction, and interpretation were queried as the subject of the evaluation.

Secondly, the question arose of which methods and tools to activate students in partaking in the lecture (e.g., by suggesting experimental parameters or speculating on the outcome of experiments) are regarded by students as a suitable way to interact with the lecturer and influence the experiments. The general assessment of experiment selection and implementation was also included in this set of questions in order to obtain feedback on the quality of knowledge transfer.

The result is presented below, with six selected experiments that are more or less logically coordinated and build on each other, as well as selected results on audience response systems integrated and the overall evaluation by students, giving evidence on the perception of the experimental lecture. In addition to materials science motivation, the transfer of the teaching content and the experiment-supported activation in the digital space are presented. Here, it was possible to rely on experiences from teaching with blended learning [13].

2. Materials and Methods

First, the process of an experimental lecture in the digital space is described with a focus on technical equipment and execution, student activation, and audience response. Afterwards, the lecture boundary conditions are explained as well as the evaluation questionnaire for students. The latter is intended to provide an insight into how and whether the transfer of an experimental lecture to the digital space was successful from the student perspective.

Second, subject-related experiments from the field of dental materials are explained. All selected experiments were in general planned for a face-to-face lecture with students and could be performed by the students themselves without major laboratory equipment. With high school and basic scientific knowledge, it should be possible to derive a hypothesis for the respective expectations of the experiments. Furthermore, it should be possible for the students as a group to give an explanation for the expectations of the experiment's outcome.

2.1. Workflow of an Experimental Lecture in the Digital Space

Technical Equipment

For the synchronous lecture, Zoom (version 5.4.6, San José, CA, USA) was used as a digital communication platform. In principle, alternative systems (e.g., BigBlueButton, MS Teams, WebEx, or similar) that allow sharing a camera image and at the same time sharing a presentation or PC screen with the students were also possible. It was also advantageous to have a system that allows breakout sessions.

The computer used was a Microsoft Surface Pro 7 (Intel® Core™ i5-1035G4 CPU @ 1.10 GHz, 1498 MHz, 4 cores, 64-bit, 16 GB RAM; Microsoft, Albuquerque, NM, USA) with Microsoft Windows 10 Education. The presentation was created using Microsoft Office Professional Plus 2016 (64 bit)—PowerPoint. A USB-RJ45 adapter and 1000 Gbit

network connection was used for stable internet connection. For easier presentation, a second screen was connected to the computer and the presentation was run in speaker mode during the online lecture. The setup in the lab was divided into the technical backend, the experimentation area, and the preparation area (Figure 1a).

For flexible video camera control and high freedom of movement, the plug-and-play video conferencing system Logitech Group (Logitech, Lausanne, Switzerland) connected via USB with two extension microphones was used. The system allows pre-saving up to 5 camera positions with up to 10 \times optical zoom. These positions can be selected by means of a remote control with only one keystroke and are thus automatically moved. The system offers HD video resolution and focuses automatically. The following camera positions were selected and saved in advance (Figure 1b–e): 2 close-ups (1 \times for the work area (e), 1 \times for a storage area of a longer-lasting experiment (d)), a semi-close-up of the experimental area (c), a wide shot of the laboratory working area (f), and a wide shot of the laboratory area with refrigerator and heat cabinet (b).

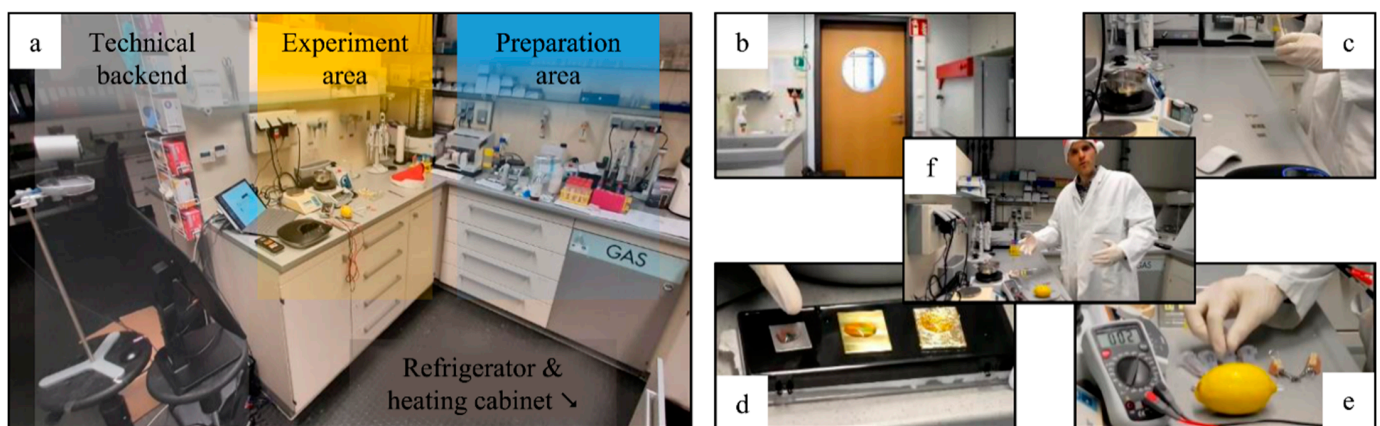


Figure 1. Photograph of the laboratory with highlighted areas of the technical equipment, the experimentation area, and the preparation area (a). Video snapshots from prepared camera positions for continuous observation of experiments and lecturer: heating cabinet (b), full experimental area (c), maximum zoom experiment (d), medium zoom experiment (e), and lecturer view (f).

In order to obtain parameters for the experiments and test procedures to be selected from the students themselves, two online blackboards, namely, padlets (www.padlet.com, 14 December 2020), were created in advance of the experimental lecture to allow students to give direct feedback or suggestions for the experiments. Furthermore, one padlet was used for the expectation query during another experiment. The structure of the respective padlet pages is explained in more detail in the corresponding experiments. Students could access the padlets via QR code (on PowerPoint slides) or hyperlink (posted in a Zoom chat) at the corresponding time. Furthermore, audience response was obtained through the voting function of Zoom as well as via direct questions to the auditorium and direct requests to speak after unmuting the respective students. Following the lecture, an evaluation was conducted with the online platform for academic teaching and learning used by TU-Dresden (<https://bildungsportal.sachsen.de/opal>, 14 December 2020).

2.2. Study Design

A lecture from the Materials Science course at Technische Universität Dresden served as the experimental unit. The lecture on dental materials, including a seminar, is an obligatory part of the course and is scheduled for the 9th semester of diploma studies or the 5th semester of the bachelor's degree. During the experimental lecture 14 students (and 3 co-workers) were present as participants of a Zoom meeting the whole time. This corresponded to a proportion of 54% of the students registered at the beginning of the semester, of which 2 were enrolled in mechanical engineering, 1 was enrolled in dental medicine, and the rest were enrolled in materials science. The final exams were taken by

18 students. From this point of view 78% of the students' partaking in the exams visited the experimental lecture at the halfway point of the semester.

A midterm and a final evaluation of the lecture series were submitted anonymously by 7 students. The broadcasted experimental lecture was evaluated by a separate questionnaire, which was answered anonymously by 6 students in the period right after the end of the event and the following 2 weeks. The questions asked allowed free text (FT) answers or grade assignments (GA) according to the German school grading system: very good, good, satisfactory, sufficient, poor, insufficient. The following questions were asked in the evaluation:

- Please rate the technical implementation of the experimental lecture in the digital space. (GA)
- Which comments do you have on the technical implementation? (FT)
- Rate the activation of students (padlet, chat, surveys, feedback via microphone, etc.). (GA)
- What did you particularly like about the experimental lecture? (FT)
- What did you not like about the experimental lecture? (FT)
- How would you rate the selection of experiments in general? (GA)
- How would you rate the relationship of the experiments to the respective explanation of the fundamentals? (GA)
- What comments do you have on individual experiments? (GA)

The evaluation results were analyzed by the OPAL internal analysis tool, which calculates mean values from the grade assignments and visualizes the number of students and their responses for each question. Emphasis was put on the verbal feedback of the students in order to assess the subjective effect of the experimental lecture as a substitute for a real self-learning experience.

2.3. Subject-Related Experiments from the Field of Dental Materials

In the following, the subject-related experiments from the field of dental materials are explained with a detailed description of the procedure.

2.3.1. Experiment I—Bye, Bye Teeth—Teeth in Non-Aggressive and Aggressive Liquids Materials

- Animal teeth (especially suitable incisors from buffalo with a length of 4–6.5 cm; purchased from www.animalskeletons.de 14 September 2020, Gladbeck, Germany)
- 50 mL reaction tubes with screw cap
- Reference liquids and solutions:
 - ddH₂O (arium[®] pro, Satrius Lab Instruments GmbH & Co KG, Göttingen, Germany)
 - Ethanol (VWR Chemicals, Darmstadt, Germany)
 - Artificial saliva (according to DIN EN ISO 10993-15 [14])
 - Simulated body fluid (mSBF according to Kokubo et al. [15])
- (Presumably) aggressive solutions:
 - 1 M HCl (Sigma-Aldrich, St. Luis, MO, USA)
 - 1 M NaOH (Roth, Karlsruhe, Germany)
 - 1 M Citric acid (Sigma-Aldrich, St. Luis, MO, USA)
 - Coca Cola[®] (The Coca-Cola Company, Atlanta, GA, USA)
- Fine balance (+/− 10 mg; YA102, OHAUS Coop., Parsippany, NJ, USA)
- pH-indicator strips (MQuant, non-bleeding, pH 0–14; Merck KGaA, Darmstadt, Germany)
- Photo documentation, ruler
- Optional:
 - Hardness meter (Shore D LX-D digital durometer, gainexpress, To Kwa Wan, Hong Kong)

Procedure and Duration

To carry out the experiment, it is essential to start storing the teeth a few weeks (in the present case for 6 weeks) before the final evaluation. It is suitable, for example, to use this experiment as a prelude to the lecture series for motivation and to carry out the final measurements in the middle or at the end of the semester.

In face-to-face lectures, it is suitable to let the students carry out the measurements of the initial mass of the teeth and pH values of the solutions themselves. The optional hardness measurement at various points (enamel or dentin) can also be carried out by the students themselves using a portable hardness tester. In addition, it is suitable to have the students make a photo documentation.

Prior to the experiment, a padlet can be used to query suitable examination methods and parameters with which the effects of the liquids on teeth can be observed. In addition, the query of fluids that serve as reference and fluids that are expected to cause a visible or measurable change can be carried out via a padlet or other web-based survey software.

The opening experiment is documented, e.g., by video, or might be part of a synchronous lecture as well. All teeth are weighed and photographed from the front and back before being incubated in the liquid. During the course of the semester, documentation by means of photographs is advisable.

The evaluation requires approx. 3–5 days before the synchronous experimental lecture to remove the teeth with tweezers from the liquids in order to dry them to mass constancy. This is when masses of the dried teeth after incubation can be determined in the live lecture. Photo documentation and optional hardness measurements can be performed with ease live as well. The pH values of the solutions after removal of the teeth can also be quickly analyzed. If these values are entered into an Excel spreadsheet that is integrated into the PowerPoint presentation, a comparison of the change in mass, pH, and hardness can be made immediately.

Here it is advisable to let the students formulate the evaluation or hypotheses for the outcome of the experiment themselves and let them discuss as a group first. Depending on the desired depth of explanation, the background for the results can be explained subsequently in one or two PowerPoint slides according to the previous discussion.

2.3.2. Experiment II—Brush or Away—Protective Toothpaste

Materials

- Egg (from a grocery store)
- Pencil and screw-cap vessel in which the egg fits
- Toothpaste (fluoride containing; e.g., Mara expert Fluorid Gelee (containing Natrium-fluorid (12,300 ppm F⁻; Hager & Werken GmbH & CoKG, Duisburg, Germany)
- Acetic acid (vinegar essence 25% acid from a grocery store) or a concentrated acetic acid ($\geq 99\%$; Sigma-Aldrich, St. Louis, MO, USA) diluted to 5 v/v-%

Procedure and Duration

First, a line is drawn with a pencil along the smaller circumference of the egg's circumference. Even after the experiment, when the eggshell is (partially) dissolved, the two halves (treated and untreated) should still be identifiable. Then one half of the egg, in this case the low (rounder) part, is covered with the fluoride-containing toothpaste (fluoride gel). The egg is stored for 24 h this way. In case of drying out, the toothpaste can be replaced from time to time. The toothpaste is rinsed off carefully under running water so that no toothpaste remains. The egg is placed afterwards in a vessel and completely covered with 5 v/v-% acetic acid [16]. The most visually attractive part is from 5 min to 1 h after starting incubation. The experiment may proceed with up to 24 h of storing the egg in acetic acid. The live lecture may be used to start incubation or may take place when the egg is removed from the acid. In both cases the condition of the shell at the toothpaste-treated and untreated sites can be discussed together with the students and the translation to the teeth can be deduced.

As an add-on, it is possible to use an egg whose shell has been completely dissolved (about 48 h storage in acetic acid) and clean it with water and dry it with a tissue. Subsequently, a drop of fluoride toothpaste (transparent fluoride gels are most suitable) is placed locally on the egg skin and stored for another 24–48 h. To prevent drying, the gel drop can be replaced from time to time. Finally, the gel is rinsed thoroughly. Re-mineralization can be discussed in a following lecture, for example.

2.3.3. Experiment III—Very Impressive—Dental Impression and Model Materials

- Materials
- Screw-cap vessels with approx. 150 mL capacity
 - Teeth for taking impressions (particularly suitable: equine molars approx. $4 \times 4 \times 2 \text{ cm}^3$, purchased from www.animalskeletons.de 14 September 2020, Gladbeck, Germany).
 - Alginate impression material (algistar classic, Müller-Omicron GmbH & Co. KG, Lindlar, Germany)
 - Two-component silicone (Silon 25 ABT, Schuhmann-Silikone.de, Dresden, Germany)
 - Commercially available plaster (gypsum) and wax (candle wax) from retail stores
 - Tap water (no ddH₂O, otherwise the setting reactions are delayed)
 - A crucible and a heating plate (Hei-Tec, Heidolph, Schwabach, Germany) for liquefying the wax
 - Optional:
 - A heating cabinet to accelerate silicone crosslinking
 - A refrigerator to accelerate wax hardening
 - NaCl (Merck KGaA, Darmstadt, Germany) to accelerate the plaster-setting reaction

Procedure and Duration

First, the alginate impression material is mixed with water according to the instructions (in the present case: 2 spoons of water (40 g) were added to 2 spoons of powder (19 g)). It is important to pay attention to the exact time when the teeth are pressed in so that the silicone and the alginate are not yet too solid. A short phase of curing must then take place (for alginate approx. 1 min). The tooth can be removed once the impression material is cross-linked. Now the impressions, i.e., the negatives, can be filled with a model material to produce a positive of the tooth. For this purpose, the candle wax is heated to approx. 70 °C on a hotplate and poured into the solidified impression material. The candle wax solidifies according to the model size within approx. 15 min. This process can be accelerated by storing it in a refrigerator. The two-component silicone is mixed in the ratio of components of A:B = 10:1. The time of silicone polymerization is approx. 30 min and can be significantly reduced by storing in a heating cabinet at approx. 40–65 °C. The plaster is mixed with tap water according to the manufacturer's instructions and poured into the alginate impression mold. The setting reaction takes approx. 60 min and can be accelerated by adding table salt to the tap water.

The wax, silicone, and plaster models can then be removed from the alginate impression material and compared with the tooth used for the impression. It is also useful to store the alginate impression at ambient conditions (for a few weeks) to illustrate the shrinkage owing to the loss of liquid.

2.3.4. Experiment IV—When the Spark Jumps Over—Galvanic Elements

- Materials
- Lemon (from a grocery store)
 - Metal samples
 - Aluminum plate or foil, zinc nail (or galvano-zinc-plated steel nail), steel nail, brass nail, (all available at a hardware store)
 - Titanium dental implant (may be obtained as a sample from a manufacturer)

- Partial denture with stainless steel framework (may be obtained as a sample from a manufacturer)
- Multimeter (20–2000 mV, Voltcraft VC 130, Conrad, Hirschau, Germany)

Procedure and Duration

In advance of the experiment, the students can use a padlet (timeline) to create a hypothesis about the order of the different materials from base to noble. The joint editing option in the padlet allows corrections to be made or comments to be added (e.g., on different states of the materials, such as aluminum with and without a passive layer). Subsequently, the potentials of the metals are measured in relation to each other. Here, care must be taken to ensure a high-impedance voltage measurement, since any reactions that occur can falsify the potential measurement. The potential measurement is best started with the least noble material at the negative pole of the multimeter and any other metal at the positive pole. Keeping the least noble metal at the negative pole, all further potentials are indicated as positive values and a practical galvanic series can be easily determined. The students can add the measured values directly in the padlet for the individual materials as comments and correct the order if necessary. Subsequently, the reactions occurring at the anode and cathode as well as the sequence of the materials can be discussed. Special attention can be drawn to any deviations from the electrochemical voltage series under standard conditions.

2.3.5. Experiment V—No Need for Contact—Evans Drop

Materials

- Metal specimens (approx. $30 \times 30 \times 1.5 \text{ mm}^3$):
 - Iron or steel plate (no passive or stainless steel should be used)
 - Iron/steel plate sputtered with gold (using a MED020 small coating machine, BAL-TEC, Pfäffikon, Switzerland)
 - Iron/steel plate manually coated with a layer of gold leaf using a diluted glue
- Testing solution:
 - 0.5 M NaCl (Merck KGaA, Darmstadt, Germany) and 3 mM $\text{K}_3[\text{Fe}(\text{CN})_6]$ (potassium hexacyanoferrate(III); Fluka Honeywell, Schwerte, Germany) in ddH₂O and phenolphthalein (“D,” indicator $8.3 < \text{pH} < 10$; RAL Diagnostics, Martillac, France) in a dropper bottle
- Petri dishes and a pipette or disposable plastic dropper

Procedure and Duration

The solution should be prepared fresh (on the day of the experiment). To do this, 3 g NaCl, 0.1 g $\text{K}_3[\text{Fe}(\text{CN})_6]$ *rotes Blutlaugensalz* and 1 drop of phenolphthalein is added to 100 mL distilled water. The solution is pipetted onto the plate specimens as a larger drop in each case (drop diameter approx. 10–15 mm) [17]. Subsequently, the color change of the pH indicator, the color change of the potassium hexacyanoferrate(III) to form the Prussian blue complex, and the rust ring formation can be observed over a few minutes. The result can be seen particularly clearly after about 60 min and can be discussed together with the students via a live discussion and an explanatory PowerPoint slide. Of particular interest here is the observation of the type of corrosion in contrast to experiment IV.

2.3.6. Experiment VI—Give Me Candy. Give Me Cake. Give Me Something Sour to Make!—Bacteria as Acid Manufacturers

Materials

- Sterile device for tacking a saliva sample
- 15 mL reaction vessels with screw cap (6 ×)
- SSL broth for the cultivation of acid-tolerant microorganisms (e.g., lactic acid bacteria, acetic acid bacteria, yeasts, and molds from soft drinks) (Döhler, Darmstadt, Germany)

- Glucose (Sigma-Aldrich, St. Louis, MO, USA)
- Optional:
 - A cookie or other sugar-containing cake (finely crushed)

Procedure and Duration

The experiment is performed with slight changes to a TV broadcasted experiment [18] in accordance with the bacterial broth user manual [19]. It requires a preparation of about 3 days before the actual evaluation. First, the SSL broth is divided among six reaction vessels. Then, a saliva sample is added to 3 of the 6 solutions. Subsequently, the samples are stored in a heating cabinet at 25–29 °C for the proliferation of bacteria from the oral cavity for 48 h. Afterwards, about 1 g of glucose and 1 g of ground cookie are added to one broth with and without saliva sample, respectively, and stored in the heating cabinet for an additional 24 h. During the experimental lecture, the saliva sampling part and the addition of the sugar-containing materials can be shown, and then the prepared samples are used for evaluation. Finally, the pH value of all six liquids is determined with the pH measuring strips and the result is discussed with the students. Here, too, an explanatory PowerPoint slide can be used for the sugar reactions that occur in the presence of lactic acid bacteria.

3. Results

3.1. Workflow of an Experimental Lecture in the Digital Space, Students' Participation, and Students' Perception

The carrying out of the course from the laboratory did not cause any major difficulties, but actually allowed a slightly more flexible delivery than would have been possible with students in an auditorium. The lecture was carried out according to the scheduled time schedule. The camera positions stored in advance were selected with the remote control according to the area of interest (preparation, experiment, detailed observation, explanation by lecturer). In addition to the continuously broadcast video image, a screen was shared on which either the PowerPoint presentation with a short teaser for each experiment or a slide for explanation was shown, or the current status of padlets in a web browser was presented. The padlets were used to allow students to work together in one document, flow chart, or sketch board. This way it was always possible for the students to follow both the lecturer and the experiment and to follow the slides or to see the padlet as an audience response tool.

Since the students were not made aware in advance that a survey would be conducted after the event, participation was not biased. It should be noted, however, that some experiments had already begun before the day of the experimental lecture and/or suggestions for carrying them out had already been requested, which might have built up a certain degree of suspense.

The question of the perception of the digital experimental lecture (as a demonstration lecture or as an activating practical course without physical experience) was investigated by means of a questionnaire. The evaluation survey among the students (using OPAL) showed that the technical implementation of the experimental lecture in the digital space was rated as very good by 67% of the participants and as good by 33% of the evaluation participants. As a remark, the use of QR codes and additional classical hyperlinks was pointed out, because in one case the QR codes were not readable with a smartphone.

Furthermore, the technical methods for activating the students and broadcasting the lecture were evaluated as follows: "The technical implementation was really super, also with the panning camera and the pre-programmed settings," "It was really incredible how well the switching between cameras worked—chapeau. Internet was also stable," and "I found everything well solved. Nobody can do anything about the stability of the internet connection." In response to the free-text questions about what the students liked or did not like about the experimental lecture, they responded as can be seen in Table 1. No answers were given to the question of what advice the students had about individual experiments.

Table 1. Free-text answers of students after participating in the experimental lecture.

What Did You Particularly Like about the Experimental Lecture?	What Didn't You Like about the Experimental Lecture?
<p>"Definitely that it existed at all. The practical reference was really fun, even if it was online. A lecture like this should be done in many more modules."</p> <p>"The will to make experiments possible despite the online situation. The setting in the lab. The illustration of lecture content by practical example."</p> <p>"The lecture was more "relaxed" and less dry than normal lectures."</p> <p>"It felt like you were "live" on site."</p>	<p>"The time pressure, which left too little time for understanding and comprehension. Maybe better to do 1–2 experiments less."</p> <p>"I thought it was really good, no criticisms."</p> <p>"I can't say anything negative about the lecture."</p>

The selection of experiments and the ratio of experiments to explanations were also rated as very good by 50% of the students, as good but with too much explanation by 33.3%, and as good but with too many experiments by 16.7% of the students. The evaluation of the participation of the students by means of padlet, chat, surveys, and feedback by microphone was rated by 50% of the students as very good and 50% as good.

In the final teaching evaluation, four of the seven participating students explicitly referred to the experimental lecture, with three citing the experimental lecture as a particular strength of the course. Here, reference was made to the aspect of the experiments as a combination of video and live events, the built-up nature, and the integration into the theoretical teaching context. Furthermore, a detailed feedback on the experimental lecture was given, which highlighted the transfer of the practical teaching unit into a digital demonstration lecture:

"Another big positive point is the implementation of the demonstration experiments. Again, you have managed to convert the demonstration experiments into a very enjoyable digital format where we can learn a lot and at the same time not get bored because it is just fun to watch them being performed. Yes, it's a shame not to do our own experiments, but this version is almost as good as it would usually be."

In addition, from colleagues partaking as listeners, there was a short assessment from experienced teachers on the Chair of Biomaterials of TU Dresden, which was shortened and translated as follows:

"This is how a lecture should be. You structured the experiments very well and conveyed the learning content in a sympathetic manner. The ratio of experiments and explanations was optimal. It was easy to follow and I think that the students will remember it for a long time. It was also great to see what is technically possible! These various pre-programmed camera settings actually make an assistant obsolete, but also shows how well you planned and thought through the entire process in advance."

3.2. Subject-Related Experiments from the Field of Dental Materials

In the following, the results of the experiments are presented very briefly. In many cases, similar setups and results can be found on the internet, which can be adapted in many ways. Thus, setups can be chosen that provide results that can be used as incentives and motivational questions for many disciplines. In the following, the focus was on the field of scientific material characterization and biomedical properties of teeth and dental materials.

3.2.1. Experiment I—Bye, Bye Teeth—Teeth in Non-Aggressive and Aggressive Liquids

In the case of the four selected reference liquids, there was hardly any effect on the pH before and after incubation or on the change in mass (Figure 2a,b). It is worth noting that storage in modified SBF led to an increase of the mass, while in all other cases the dry mass after incubation was lower than the initial mass of the teeth. In the photographs of the teeth, hardly any changes were visible to the naked eye (Figure 2c,d). The only noticeable change was that after drying (following the incubation) the teeth showed increased cracks in the enamel (Figure 2d).

Incubation of the teeth in the aggressive liquids showed mass decreases of 4 to 14 wt.%, whereby the pH values, which were quite low in the case of the acids, were clearly raised as a consequence of the incubation. They even reached the range of the physiological pH value of saliva of approx. 7.1 [20] in the case of citric acid. The strong changes in the masses were also reflected in the photographs of the teeth (Figure 2d). In the case of Coca Cola®, no erosion of the enamel or dentin was visible to the naked eye, but the discoloration was very marked and could not be removed by rinsing simply with water. With citric acid and HCl, the destruction of the enamel was very evident, and with HCl, a coarse, very solid crystalline phase was formed on the surface. Particularly striking was the severe destruction of the tooth by incubation in NaOH (Figure 2d). This was already apparent after 1 week of incubation and finally led to complete destruction, which started from the dentin, as the internal part of the tooth.

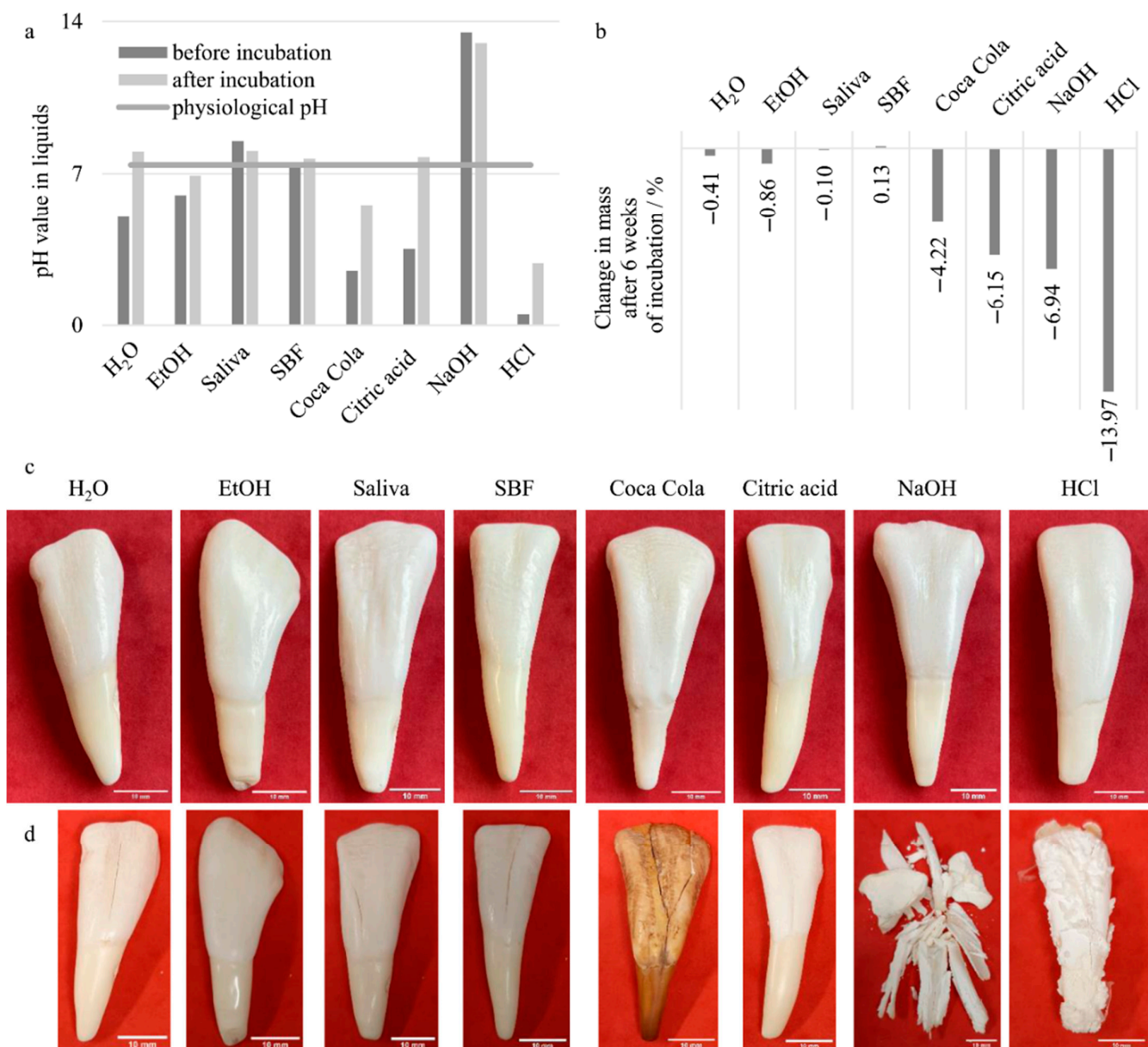


Figure 2. Measured pH-values in various liquids (double distilled water, ethanol, artificial saliva, modified simulated body fluid, Coca Cola®, 1 M citric acid, 1 M sodium hydroxide, 1 M hydrochloric acid) before and after incubation of teeth for 6 weeks (a) and change in mass of teeth during that time (b). Photographs of teeth before (c) and after (d) incubation. Scale bar equals 10 mm.

3.2.2. Experiment II—Brush or Away—Protective Toothpaste

Treatment of an egg with fluoride gel did not cause any change in the eggshell visible to the naked eye (Figure 3a–c). After rinsing off the gel, it was not possible to distinguish between the two sides or to determine the exact border (except for the drawn line). When the egg was placed in the acetic acid, gas bubbles could quickly be seen on the surface of the egg, which were very clearly delineated over the first 25–30 min and thus only visible on the untreated side (Figure 3d–f). With increasing incubation time, the gas bubble formation became more and more visible also on the treated side (Figure 3g,h). After removal from storage in acetic acid and rinsing as well as careful drying, only two small areas could be seen (and sensed) on the treated side, where the mineral phase of the shell was still present (Figure 3i,i'). The rest of the egg was very soft and could be deformed with great elasticity.

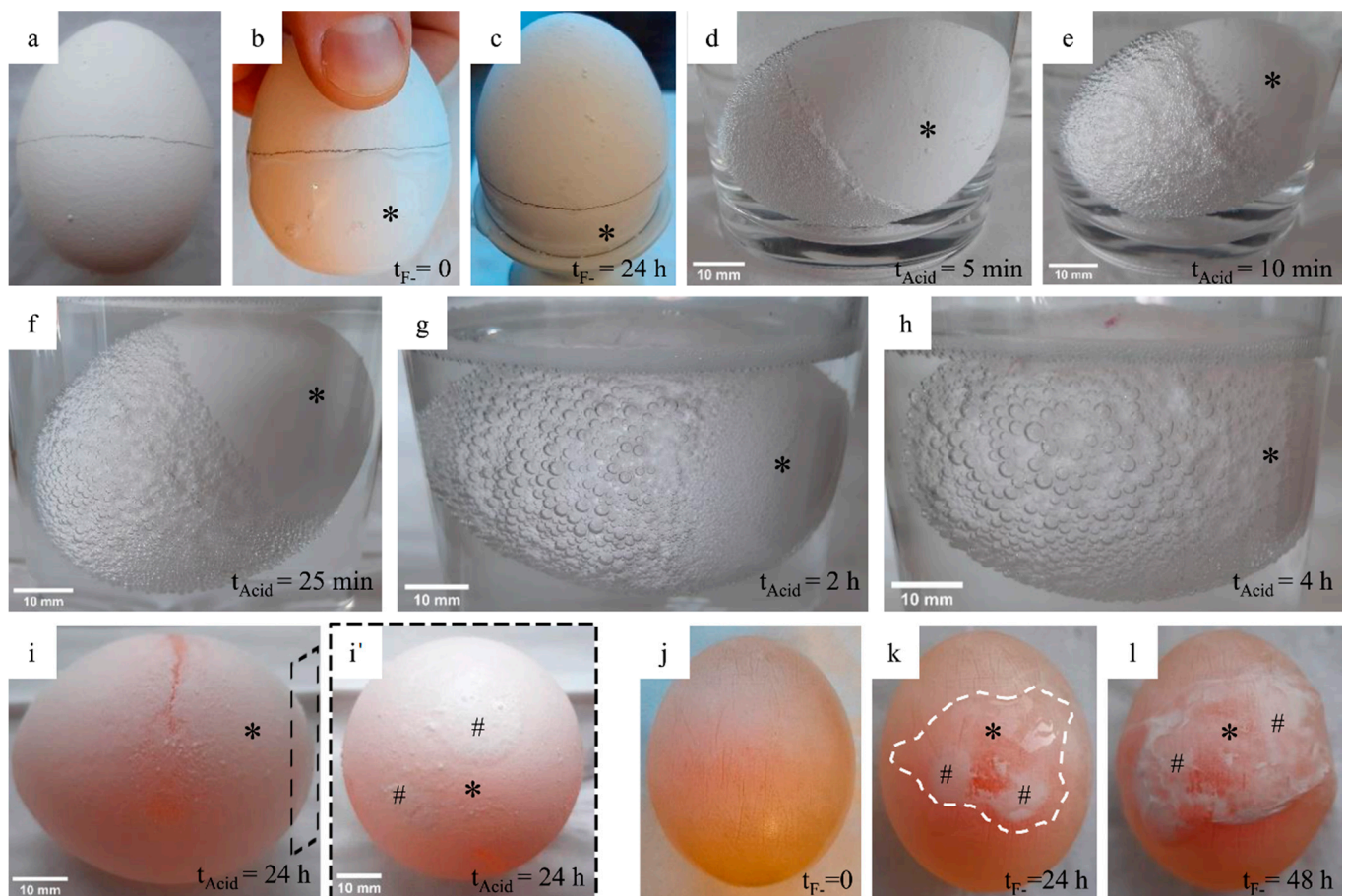


Figure 3. Photographs of an egg with horizontal line drawn (a), with the fluoride gel applied (b), and after storage in the gel for 24 h (c). Storage of the egg over 4 h in acetic acid (d–h). Since storage in the vessel leads to optical distortion, the side treated with fluoride in each case was marked with an asterisk. Photograph of the egg after removal from the acetic acid after 24 h and rinsing with water and gentle drying (i). The black dashed frame in (i) indicates the view of (i'). Detailed image of the treated side showing the only two areas still mineralized (indicated with #). Extension of the experiment: egg completely freed from the mineral phase after 48 h storage in acetic acid (j). Egg with fluoride drop (*, outer border marked with white dashed line) after 24 h (k) and 48 h (l) and newly formed mineral phase (#).

An extension of the experiment was prepared by further storage of the egg in acetic acid (for about 48 h in total). The mineral of the eggshell was dissolved completely and the egg was more translucent. After applying a drop of fluoride gel, a re-mineralization could be seen over a period of about 48 h (Figure 3k,l). This mineral also led to a clearly noticeable local hardening of the egg membrane.

3.2.3. Experiment III—Very Impressive—Dental Impression and Model Materials

The preparation of the impression material was subject to a strict time sequence of only a few minutes, which could be easily observed from the color changes of the alginate-based impression material (described in the instruction manual). The great elasticity of the alginate after gel formation allowed the teeth to be demolded even if undercuts were present to a certain extent (Figure 4a,a',a''). In this case, loss of the mold might be expected if the model material was to be demolded without damage. Alginate setting took place in a period of about 5–10 min, which provided an opportunity for explaining the sol-gel transition during the alginate setting. Subsequently to the demolding of the teeth from the alginate negative, the model materials were prepared and filled in the negatives. All three model materials—silicone (Figure 4b,b'), plaster (Figure 4c,c'), and wax (Figure 4d,d') required a period of about 15–60 min to cure. This time was used to explain the chemical reactions (plaster curing, addition polymerization of silicone) and physical processes (phase transition of the wax). In the case of plaster a significant cooling of the alginate mold was reported to the students. When the wax cured, a shrinkage at the filling position of the alginate mold was clearly visible. It is advisable to carry out other experiments and subsequently perform the demolding of the silicone, wax, and plaster model from the alginate (Figure 4b''–d'').

An important circumstance for model extraction was derived from a freshly prepared and a dried alginate negative (Figure 4e,e') in comparison with the originally molded tooth (Figure 4e''). Here it can be seen that immediate model preparation from the alginate mold without exposure to elevated temperatures was necessary, since the drying of the alginate mold led to considerable shrinkage and no dimensionally accurate model could be prepared.

3.2.4. Experiment IV—When the Spark Jumps Over—Galvanic Elements

When measuring the potentials between the different metals and alloys, care needed to be taken to achieve a constant value. The aggressive citric acid could have caused corrosion reactions, which in turn could result in distortions (Figure 5a). Therefore, the measurements needed to be carried out immediately. The measured values could be seen directly by the students in the selected video stream (Figure 5b,c). The sequence of metals chosen by the students was initially aluminum—zinc—steel—brass—titanium—stainless steel. The first measurement already showed that the lowest potential under the selected conditions was present in zinc, which the students were able to change themselves in the padlet to the correct galvanic order (Figure 5d), allowing the lecturer to continue the experiment.



Figure 4. Screenshots taken from the video stream during preparation of tooth impressions and the fabrication of tooth models from various modeling materials. Alginate impression material (orange and cyan) during mixing with water (a), impression of an equine molar (a'), and after the demolding of the tooth (a''). Mixing the two-component polyaddition silicone (b), pouring it into the alginate negative (b'), and demolding the silicone model (b''). The plaster is mixed with water (c), the alginate negative is filled with the plaster (c'), and the plaster model is demolded with the loss of the alginate mold (c''). Wax before heating to approx. 70 °C (d) to fill the alginate negative (d') and comparison of the wax model with the original tooth after demolding with loss of the alginate mold (d''). Comparative presentation of the tooth and alginate mold immediately after demolding (e), after storage at room temperature for >4 weeks (e'), and the comparison of the dried alginate mold with the originally demolded tooth (e'').

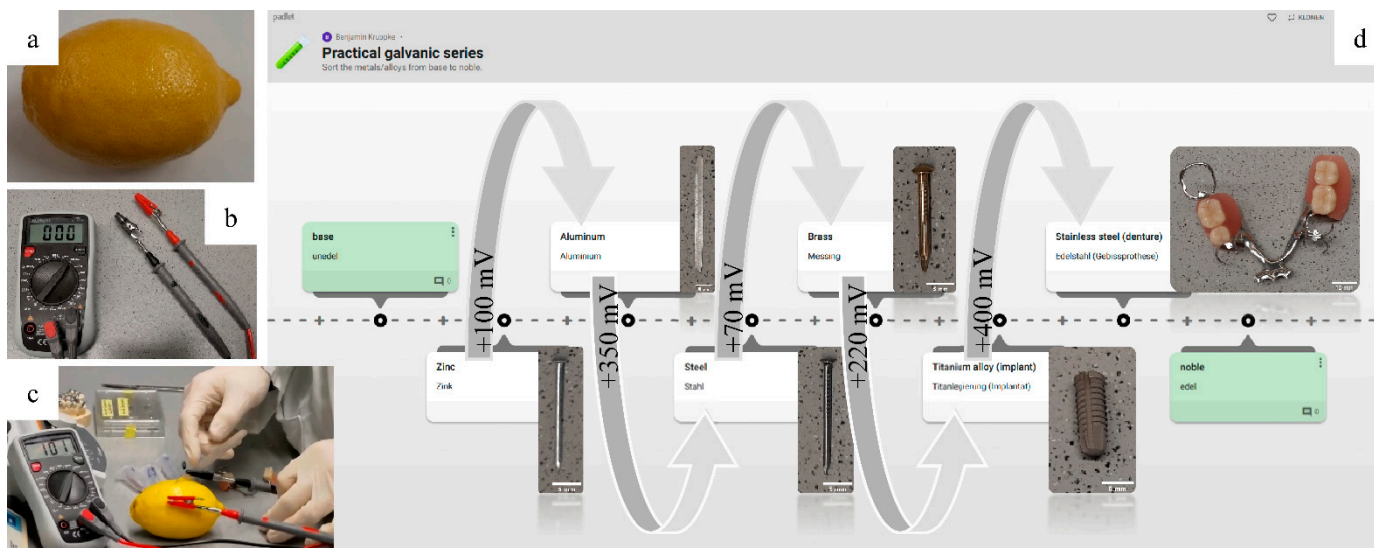


Figure 5. Photographs in the initial state: lemon as an acidic environment serves as the electrolyte (a), high-impedance voltmeter (b), and video snapshot taken from the synchronous lecture during the measurement of the potential between zinc and aluminum (c). The padlet as screenshot (d) shows the materials entered by the students themselves and the order between base and noble according to their assumption. The photographs of the test materials and the respective measured potentials (as approx. values) between the materials (indicated by arrows) were added subsequently.

3.2.5. Experiment V—No Need for Contact—Evans Drop

The metal plates without surface treatment and with gold sputtering were very smooth at the beginning, whereas the gold leaf could not be applied as an ideal single layer and thus showed some warping (Figure 6a–c). Immediately after placement of the drops (Figure 6d), the liquid was transparent and the surface of the metal plates was clearly visible. The process of multicolored discoloration of the solution and the metal surface, respectively, was immediately visible to the students in the detailed image (Figure 6d'). In this figure it can be seen, and it should be noted, that the inclined underground for the alignment to the camera was disadvantageous, because the typical ring structure of the reaction products was not formed. With the naked eye it could be seen already after a few minutes and particularly clearly after about 1 h that three areas marked in color appeared. On the one hand, there was an outer pink-violet area at the drop edge or where the drop was very flat, a ring-shaped reddish area, and a dark blue center. These three areas could be seen in varying degrees on all three metals (Figure 6a'–d'). In particular, the blue region in the center was very evident on the gold-coated metal samples.

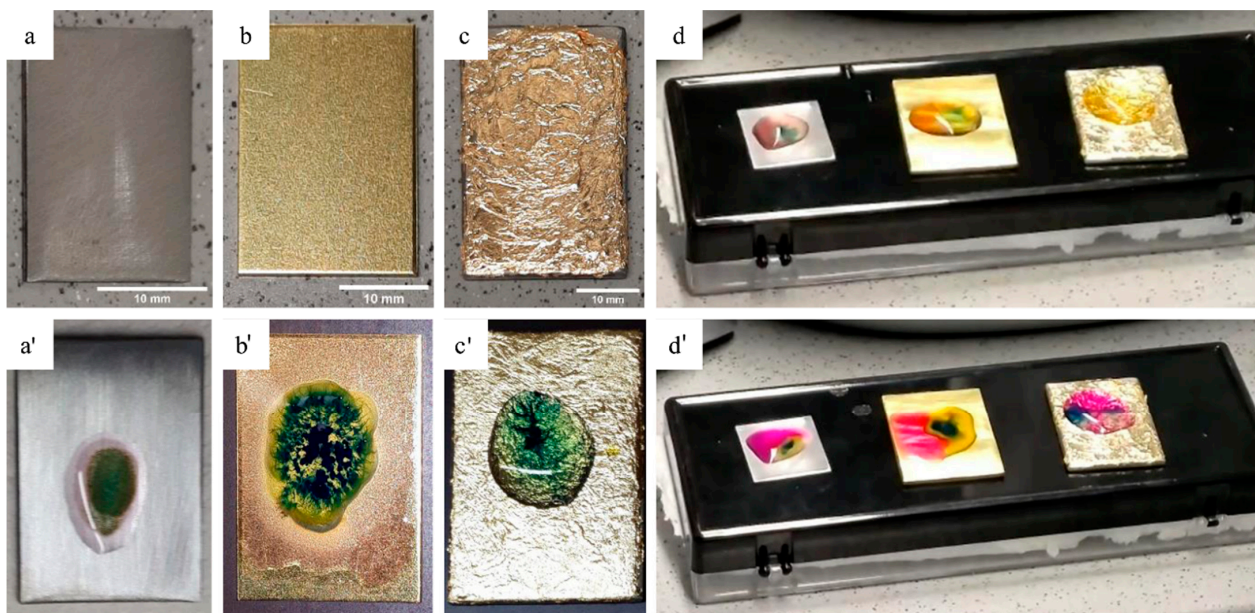


Figure 6. Photographs of initial states of steel plates: blank (a), with gold sputters on the surface (b), and with a plated gold surface (c). Steel plates after placing the Evans drop and storage for approximately 60 min (a'–c'). The samples shortly after beginning (d) and at the end of the experiment (d') during the synchronous lecture in the maximum zoom of the broadcast video.

3.2.6. Experiment VI—Give Me Candy. Give Me Cake. Give Me Something Sour to Make!—Bacteria as Acid Manufacturers

The broth was translucent at the beginning of the experiment and did not change this state during storage in the heating cabinet. By adding the saliva sample, a turbidity in the broth could be seen after about 48 h of storage (Figure 7a). However, this turbidity was not accompanied by a change in pH (Figure 7b,d). After dividing the two solutions into the three reaction vessels each (Figure 7c) and additional storage for 24 h in the heating cabinet, a slight decrease in pH was seen in the case of the cultured saliva sample and a more pronounced decrease was seen in the case of the cultured saliva with glucose or crushed cookie in the broth (Figure 7d). In all other cases, the pH value did not differ from the initial pH value.

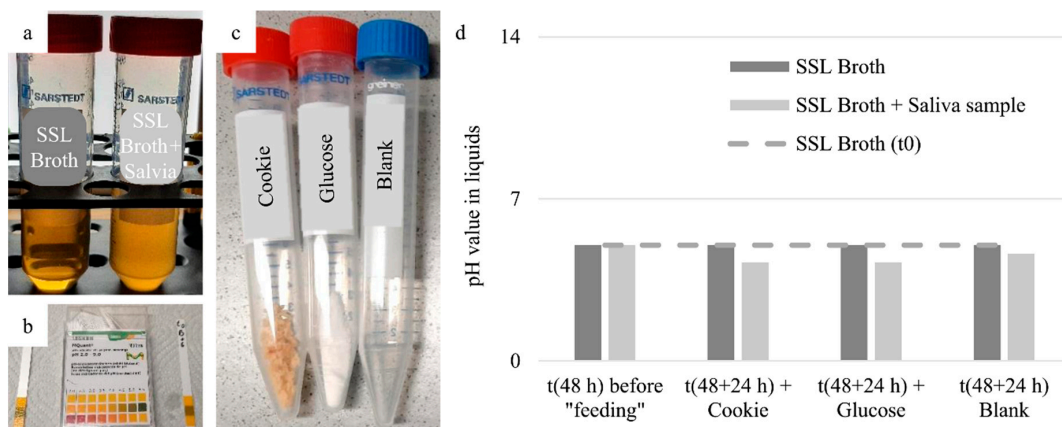


Figure 7. Photographs of the broth after 48 h of storage in the heating cabinet; left: blank, right after cultivation of the bacterial sample from the oral cavity (a). pH measurement of the solutions from (a) using pH measuring strips (b). Prepared reaction vessels (prepared in duplicate) with ground cookie (as sugar source), glucose, and for the plain liquid (blank) (c). pH measurements after the respective experimental phases (d): SSL broth (t0) corresponds to the initial condition of the broth, SSL broth after 48 h with and without saliva sample (before “feeding”), as well as this broth and a further 24 h of storage following division among the reaction vessels with crushed cookie, glucose, and the (sugar-free) reference.

4. Discussion

4.1. Workflow of an Experimental Lecture in the Digital Space and Students' Perception

The goal was not to present a series of experiments using current broadcasting technology and team-meeting tools, but rather to achieve active participation by the students in order to shift the perception of the students. This perception should have given the course a hands-on experience with an awareness of intervention and discussion possibilities. In addition, subconscious attention to the behavior in a laboratory should have been kept by continuously following the presented experiments. The starting point for the lecture was face-to-face teaching, which was carried out as a regular lecture in a lecture hall. Thus, the experiments (except for a few in-depth sub-examinations) were planned to be carried out in the context of such a course. The aim was to let the students perform the selected experiments themselves with a few simple tools. This part had to be transferred to an experimental lecture presentation. Furthermore, an aim was to allow students to derive a hypothesis for the respective expectations from their school knowledge and basic scientific skills and, if necessary, to be able to formulate an explanation for the experiment's outcome in the group. This part of the experimental lecture should have survived the transition from classroom teaching to the digital space without limitations.

Previous studies focused on the effect and activation of university applicants through an internet-based blended learning module [13]. It was shown that it is possible to attract particularly qualified and motivated students to the university's biomedical curriculum. In the current case, it was the activation of students who were already at the university, which should have led to a more active participation and audience response in contrast to classical and rather unilateral lectures. The transfer to a digital synchronous (experimental) lecture enables the combination of a PowerPoint slide-based introduction part for each experiment and the precise description of the tasks (as well as expectation queries) for the individual experiment sections. Furthermore, with a suitable video and web communication technology, the immediate and easily comprehensible documentation of the experiments is possible. For this purpose, it is suitable to have the lecturer explain and execute the experiments and to have another assistant take care of the technical coordination (switching slides, activating and deactivating the online presentation to focus on the video image, taking care of web-based audience response systems (ARS), etc.).

Audience response systems play an important role in students' activation and participation in digital classes, as the barrier of unmuting the microphone is often too high to gain substantial discussions during synchronous lectures. But to not only use audience response systems in terms of a fun and anonymous tool [11,21], the pedagogical goal was to strengthen students' perception of being part of the experimental procedure. Therefore, it was necessary to show students that an experiment consists of more than only pipetting liquids to another or weighing masses before and after. For this reason, parameters and possible research methods were requested for some experiments weeks before they were conducted, and the same was done with expectation queries, which were carried out in advance of the experiment. According to the research question about which methods and tools to activate students in partaking in the lecture were regarded by students as a suitable way to interact with the lecturer and influence the experiments, it can be concluded from the feedback of the students, who all rated the tools as very good and good (without further comments), that it does not depend on the extent of the methods or different platforms, but rather that a simple setup is sufficient that allows for asynchronous as well as synchronous communication. Owing to the group character of the chosen audience response systems (e.g., Padlet), the fear of a wrong answer while all others were correct could be reduced [12], since these are not merely knowledge questions. The immediate peer feedback, which is not directly addressed to and by the lecturer, was shown to be a particularly beneficial element of digital courses [22], even with respect to inclusion and lowering learning barriers for people with disabilities [23,24]. This was evaluated as an added value compared to traditional lecture-hall teaching.

Based on the question of whether the transfer of the experimental lecture into the digital space was successful, the student perception must be analyzed in more detail. There is no doubt that the audience response systems and the way the experiments were carried out were positively perceived, and several students independently concluded that it was almost as if they had been live on site. In this context, it must be taken into account that many practical courses in engineering studies are carried out in groups anyway, which means that only some of the students are actively involved in carrying out the experiments, while others watch the procedure. Furthermore, the question is whether it is possible to maintain the attention of the students during the video broadcast. Here, the positive evaluation of the ratio of experimental to scientific background segments can be evaluated as decisive, whereby the remark to perform fewer experiments should be taken seriously.

In general, it can be concluded from the very enthused feedback of the students that above all, a high level of commitment is evaluated positively. This means that a high level of participation can be expected in terms of evaluation and discussion, even in the case of incorrectly run experiments or experiments that were largely carried out by an operator or even in advance. The real advantage is that the students do not see a pre-recorded video with time lapse, slow motion, and inserted pauses, but rather a person who takes time for them, the lecture, and the experiments. This personal component binds the attention that only synchronous events can attract. This high attractiveness of live lectures in contrast to recorded lectures was also confirmed in other studies [25–27] and was shown to be positively correlated to marks of students attending a live lecture in contrast to only watching recorded lectures [27]. It was further reported that students liked having access to recorded lectures, and mainly use them to make up for missed lectures or to prepare for assessments, but that students in most studies preferred access to live lectures [26].

4.2. Subject-Related Experiments from the Field of Dental Materials

For the subject-specific discussion, only brief explanations of the processes that take place are described below. Basically, the discussions and literature references serve as a starting point for a more profound discussion together with the students. In addition to this scientific reference, possible approaches for activating the students in the context of experiment preparation, execution, expectation inquiry, and evaluation are given in the following.

4.2.1. Experiment I—Bye, Bye Teeth—Teeth in Non-Aggressive and Aggressive Liquids

This experiment in particular is suitable for multi-level activation of the students. In the present case, before starting this initial experiment to motivate the students, a padlet was used during the first lecture of the course to enable the students to make suggestions for the liquids to be used in this tooth “dissolution” experiment (Figure 8a). In addition, they were asked for possible methods of investigation (also Figure 8a). Both questions were aimed at retrieving the students’ prior knowledge regarding materials science lectures.

In addition to the selection of the liquids, which was expanded by liquids in accordance with the experience of previous years, an expectation query was made immediately after the incubation of the teeth (Figure 8b). Here, the students were again asked to write down their expectations of the changes in the liquids and the teeth for the selected analysis methods and the various liquids.

The expectations of the students were confirmed very well in a rough approximation. All reference liquids led to no visible change in the teeth. The weight increase in modified SBF could be explained by its supersaturation with calcium and phosphate ions with regard to calcium phosphate precipitation, which can lead to mineral deposition on the surface of the teeth. This effect corresponds to the original background of SBF development, which originated in the analysis of the bioactivity of bone substitutes, namely, induced non-cellularly controlled mineral formation [15,28,29].

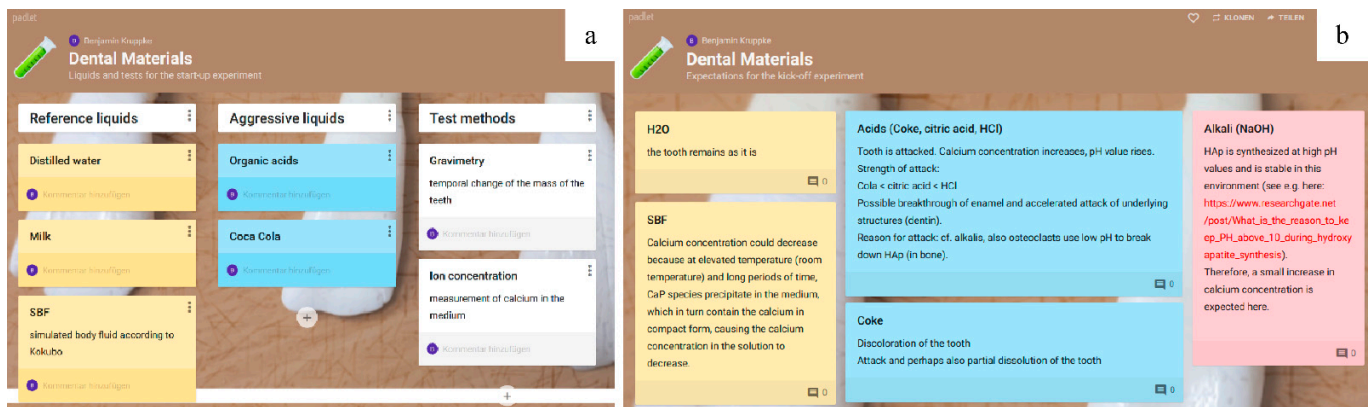


Figure 8. Padlets for active integration of students' ideas. Suggestions for liquids and test methods to be used (a) and expectation query for changes in teeth and liquids during the experiment (b). All entries were translated from German into English by the author.

In the case of liquids with a pH lower than that of saliva, dissolution of the mineral phase of the tooth can be assumed. The hydroxyapatite crystals are of nanometer scale in human teeth and only slightly larger in bovine teeth, but of the same crystallographic composition [30,31]. This mineral phase has a significantly higher solubility at a low pH value [32,33]. This can be seen from the calcium concentration of saturated solutions as a function of pH, which, in the case of hydroxyapatite, is already increased by two orders of magnitude when pH is lowered from pH 7 to pH 5. This explains the decrease in mass of the teeth as a result of long-time storage under acidic conditions.

In contrast, when teeth are stored in NaOH, the hydroxyapatite is exposed close to its stability range of pH 9.5–12 [34]. The severe damage to the teeth in NaOH is caused by the attack on the organic components of the tooth, especially of the dentin. For example, a decrease in cohesion has been observed for collagen, which is a fibrillar protein and a major component of the organic dentin matrix [35], that has undergone alkali treatment [36]. It was found that this process was primarily associated with a breakdown of the main polypeptide chains, since apart from some loss of amide nitrogen and hydrolysis of a very small number of peptide links, little chemical change in the collagen was observed. Collagen presumably goes into solution in the form of large polypeptides and not as peptides. Increased swelling of collagenous proteins at high pH values was furthermore primarily associated with the breaking of intermolecular links such as hydrogen bonds. In consequence, the organic backbone of dentin is destroyed, which might cause swelling and subsequent tooth fragmentation.

4.2.2. Experiment II—Brush or Away—Protective Toothpaste

Eggshell consists of approx. 96% calcium carbonate with a layered structural composition [37]. The remaining components include organic matrix (2%) as well as magnesium, phosphorus, and a variety of trace elements. The chemical attack on the CaCO_3 phase by acetic acid leads to the dissolution of the eggshell under formation of CO_2 . The protective effect of fluoride-containing calcium minerals in the context of caries prophylaxis has been researched and presented in many scientific publications [38–40]. Whereas in the case of the hydroxyapatite of the enamel a substitution of the OH^- ions by F^- ions is assumed, among other things [41], the formation of CaF_2 can be assumed for the CaCO_3 of the eggshell. The effect of calcium fluoride formation was described by Trautz and Zapanta as follows: *“The carbonate and the secondary phosphate, which are the enamel components most soluble in weak acid, are replaced by calcium fluoride, which is very little soluble in acid. This replacement substantially impedes the self-accelerating effect of the initial acid attack upon the enamel, viz. the enlargement of the diffusion paths which accompanies the early stages of the demineralization.”* For this reason, the protective effect of fluoride gel treatment of one half of the eggshell could be observed at least during the early stages of the experiment of egg demineralization. When

the experiment was extended by re-mineralization of the outer membrane of the egg after the mineral phase was dissolved, it is also possible—owing to the calcium contained in the egg white [42]—that new calcium fluoride could be formed with the fluoride gel treatment.

4.2.3. Experiment III—Very Impressive—Dental Impression and Model Materials

This experiment is intended to illustrate material combinations from the dental field that have no direct or long-lasting contact with the oral cavity. It is important here to point out combinations that are possible (shown here) and variants that are not usable (e.g., alginate as a directly usable negative for casting metal alloys). For this purpose, the comparison of the molded tooth with a fresh alginate mold and an already severely dried alginate mold is used. Furthermore, the students can assess the detail accuracy of wax, plaster, and silicone in comparison to the surface structure of the demolded teeth.

The alginate hardening reaction is well described in the literature [43] and used frequently in biomaterials research [44–46]. An analogy to the use of alginate in the beads of bubble tea illustrates the biocompatibility of the impression material. The time regime of alginate curing is adjusted by the manufacturer's mixture of sodium alginate, calcium sulphate, and sodium phosphate. When the powder mixture comes into contact with water, the sodium of the alginate salt is substituted by calcium ions, which means that multiple alginate molecules are now bonded to each other via the divalent calcium ions. To delay this process, the sodium phosphate is present, which is dissolved first, whereby the phosphate ions precipitate with the calcium released from the calcium sulfate as low-soluble calcium phosphate. Thus, this "removed" calcium is not available for crosslinking the alginate molecules. Once the phosphate molecules are depleted, the rapid gelation of the alginate is started.

The reactions of the model materials can be used to refresh basic knowledge, if it was part of previous studies.

Plaster curing can be described as an endothermic dissolution–precipitation reaction in which the mainly anhydrous calcium sulfate (anhydrate or hemihydrate) first dissociates in water. Subsequently, the nucleation of calcium sulfate di-hydrate occurs with the formation of elongated crystallites. The crystallization upon the incorporation of water in the crystal structure as well as drying leads to the solidification of the plaster with a slight increase in volume [47].

The hardening of the wax represents a phase transition with semi-crystalline solidification. The strong volume shrinkage is particularly evident at the filling location, making it easy to discuss the dimensional stability aspect with the students.

The polyaddition reaction of silicones has been widely described [48]. For use as an impression material, polyaddition reaction is particularly advantageous because of its high dimensional stability and the absence of side reaction products. Here, the alternative of polycondensation should be mentioned, in which low-molecular substances are formed that are either dangerous or undesirable in dental applications and lead to higher shrinkage due to their evaporation.

4.2.4. Experiment IV—When the Spark Jumps over—Galvanic Elements

The electrochemical series is a long-established system of ordering metals according to their tendency to dissolve into an electrolyte solution under electron release. However, the series shown here is not comparable to a galvanic series under standard conditions in terms of the order of the elements/alloys and the specific electrolyte. The practical aspect, which would roughly correspond to a bite into a citrus fruit, is intended to make the experiment illustrative for students and to clarify the process of hydrogen corrosion as a type of corrosion at a severely lowered pH value. Furthermore, the various metals, which are more or less relevant for dental applications, illustrate the importance of avoiding contact of these metals in the oral cavity. The (in some cases) high potential differences would lead to a serious corrosion process in the case of a metallic contact as a result of the unavoidable permanent contact with saliva as an electrolyte. A comparison with a practical

galvanic series seems particularly suitable here [49], confirming the order of the materials used, but offering a good example for reflection of the importance of alloy compositions for biomaterials due to the large number of alloys and their different potentials.

4.2.5. Experiment V—No Need for Contact—Evans Drop

The Evans drop and its electrochemical description are widely known [50], so in the present case the students should already have been familiar with the basic process from a previous corrosion lecture. Briefly, the three visible changes are discussed. First, a blue coloration can be seen in the center of the droplet. Here, the local formation of an anode occurs, in which iron as a divalent ion passes into the electrolyte. The formation of the Prussian blue complex ($\text{Fe}_4[\text{Fe}(\text{CN})_6]_3$) is considered a detection reaction for divalent iron ions. The electrons remaining in the metal during the anodic reaction move to the peripheral region of the droplet, where the localized ring-shaped cathode is formed. Here, the oxygen entering the droplet in combination with water molecules and the electrons causes the formation of OH^- ions (oxygen corrosion type). This process is more pronounced at the periphery of the droplet, since oxygen can diffuse more rapidly here than in the center of the droplet. This is the reason for the different potentials of the substrate, which in turn causes the formation of the corrosion element. The OH^- ions are in turn the reason for the pink-violet discoloration of the droplet edge owing to the pH indicator phenolphthalein contained in the electrolyte. The reaction of iron ions and hydroxide ions results in the formation of iron hydroxide and iron oxide hydroxide as a red rust ring between the two discolored areas of the droplet.

The significance of the experiment is particularly high owing to its practical relevance. Thus, corrosion is illustrated here, which occurs without the contact of two different metals and can be explained by local potential differences as a result of the variation of oxygen concentration in the electrolyte [17]. This might be considered in the field of dental materials, especially in relation to hard-to-reach areas in the oral cavity. In addition, the oxygen corrosion type can be well explained in contrast to the hydrogen corrosion type from experiment IV. The extended experiment by using a steel specimen spattered with gold and coated with gold leaf is also of considerable didactic value. The supposedly protective gold layer leads (in contrast to the expectations) to the formation of a galvanic element. This is due to a too-thin coating or small defects, with which the steel corrosion is additionally intensified. Here, for example, it is suitable to have the students discuss the processes in the Evans droplet and the observed changes caused by the gold coatings in groups in two or three parallel breakout sessions (of about 5 min). Afterwards, one student from each group reports what the observations are attributed to. This short intermediate phase can be used by the lecturer to prepare the next experiment or take a short breath. The latter is recommended, because the execution of the experiments in rapid succession under constant control of the broadcast, the camera position, etc., can be very exhausting.

4.2.6. Experiment VI—Give Me Candy. Give Me Cake. Give Me Something Sour to Make!—Bacteria as Acid Manufacturers

This last experiment is also suitable for surveys or suggestions (for materials to be tested) owing to the separate steps and necessary waiting times. The first phase of bacteria cultivation might be used to illustrate the importance of bacteria cultures as an important method for in vitro analysis of biomaterials with respect to their prevention or undesired support of biofilm formation. The proliferation of lactic acid bacteria from a saliva sample leads to a decrease in pH in those samples in which sugar is present, as glucose is converted to lactic acid [51]. In general, 50% of the glucose follows the major fermentation pathways of glucose, which are rather complex. In brief, the homolactic pathway of glucose can be represented by the use of adenosine diphosphate and inorganic phosphate to produce lactic acid, adenosine triphosphate, and water. Furthermore, the heterolactic major pathway includes glucose fermentation into lactic acid, carbon dioxide, and ethanol.

The choice of the experiment is based on a simple illustration of the fact that not only aggressive liquids, as shown in experiment I, have a damaging influence on the mineral

phase of the tooth. It demonstrates with straightforward methods that the biologically unavoidable interaction of bacteria in the oral cavity and nutrition also has an important influence on the composition of saliva (considered an electrolyte or “aggressive medium” in the context of the experiments).

5. Conclusions

Transferring an experimental lecture into the digital space requires, first of all, conscientious planning and consideration of the learning objectives of the experiments. Subsequently, the technical boundary conditions for the experiments, the broadcast of the lecture, and suitable audience response systems can be determined. In the present case, the challenge was to enable the participation of the students, even though the experiments were exclusively demonstration experiments conducted during a synchronous lecture. In the following, the three essential aspects of technology, subject content, and didactics are summarized.

The technical aspect can be concluded briefly, as with the current state of the art (laptop, second monitor, camera, microphones) and the available tools (web communication with video, audio and chat, student learning platforms, joint pin boards, and voting platforms) there is an easily accessible and flexible basis for the broadcast of synchronous lectures. There may even be a benefit to broadcasting an experiment from a real lab by having better technical equipment available and implicitly teaching laboratory skills and behavior. This may be perceived as an increase in value compared to experiments that should otherwise have been performed in a scaled-down manner in a lecture hall by students. Video broadcasting also offers the advantage that all students are equally close, which is sometimes not feasible with larger practical groups in face-to-face courses.

The technical aspects of the experiments performed can be summarized as follows. It is a great challenge to select experiments that can be completed entirely within the scheduled time. In addition, the experiments should be logically linked with each other (as in the case shown, the types of corrosion of metals and the attack of tooth substances) and idle phases should no longer occur. For this purpose, sections of explanation of experiments or discussions with students are suitable to fill these phases. To a certain extent, long-term experiments are also suitable, and their evaluation then takes place in the experimental lecture. Here, a prelude (e.g., in the form of a video of the experiment start) with asynchronous queries can provide a timely divided and thus repeated occupation with the topic.

The didactic evaluation of the experimental lecture should be based primarily on the possibilities of student activation, since this is one of the essential components of a practically conducted experiment in contrast to a seminar or lecture. Putting the focus on preparatory aspects, the questioning of expectations and the joint discussion of results makes it possible to compensate for the missing hands-on aspect to a large extent. The actual scientific learning objectives can be fulfilled by digital audience response systems if the experiments are designed accordingly. In this way, the students’ interest (according to their own assessment) can be maintained for the duration of the “only observation elements” of the experiments. The feedback indicates that students perceived the digital experiments as adequate experimentation, if a certain student influence and animating approach to the audience is integrated. This was realized using an asynchronous as well as a synchronous communication platform, whose technical implementation was rated as very good and good. The joint discussion of experimental outcomes is especially vital if assumptions on results are requested in advance and can be discussed subsequently. The selection of the experiments should be closely oriented to the content of the lecture so that the didactic role of the event is not lost by a drift in the context of the content. For a positive perception, an evaluation of the course by the students and its assessment together with the students was considered to be of great value.

6. Take-Home for Teaching

- Transfer of student experiments into a digital demonstration experiment requires reorganization of the procedure (avoidance of waiting times by, e.g., asynchronously provided videos of experiment preparation);
- Demonstration aspect is not determining (as group experiments in face-to-face also lead to spectatorship of some students)—video broadcast may be perceived as being closer on site;
- Student participation can be stimulated by asking for expectations, asking for suggestions for experiment parameters, and joint discussion of results;
- An asynchronous communication channel (joined digital pinboard) is suitable for expectation queries, collecting of suggestions, etc.; and
- A synchronous communication channel (chat, voting, unmuted microphones) is suitable for live discussion of results.

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