Smartglasses as Assistive Tools for Undergraduate and Introductory STEM Laboratory Courses

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1 Starting Point

1.1 Physics Laboratory Courses

The worldwide physics education research community seems to be in agreement that laboratory experience is an essential part of a physicist's education—during both school and university education (cf. Lunetta et al. 2005; Karelina and Etkina 2007; Hanif et al. 2009). Especially during the introductory courses at universities, the interplay between theoretical foundations and experimental reality builds up the basis for further lab work, professional work in industry, and higher education.

In this section, we want to identify key aspects of laboratory activities and experiences using the recommendations for introductory lab courses formulated by the American Association of Physics Teachers (AAPT) (cf. AAPT 2014) and a competency model by Schreiber et al. (2012) to have well-founded tools at hand to classify our own approach dealing with smartglasses as assistive tools in lab courses presented in this chapter. Using these recommendations and the competency model also allows us to formulate our approach in such a way that different institutions with their own lab course structure may identify key aspects to integrate our design.

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I. Buchem et al. (eds.), *Perspectives on Wearable Enhanced Learning (WELL)*,
https://doi.org/10.1007/978-3-319-64301-4_2

Studies show evidences that positive learning outcomes in lab courses are not guaranteed per se (cf. Hofstein and Lunetta 2004; Holmes and Bonn 2015; Wieman and Holmes 2015). For example, different aspects of the design and implementation like focusing on expert-like attitudes, developing epistemologies, or experiencing authentic scientific processes could not be reached. Other studies showed a lack of implementation of appropriate concepts concerning scientific measurement and corresponding uncertainty aspects (cf., e.g., Volkwyn et al. 2008). During the last decades, aspects of the design and implementation of laboratory courses at school or university seem to be ineffective concerning their impact on students' learning processes (cf., e.g., Wieman and Holmes 2015). During the last decades, many different approaches tried to close the research gap of missing criteria for positive learning effects in lab courses by trying to implement new design principles based on new ideas and former research work, leading to a broad variety of how to do lab courses and practice them (cf., e.g., Zwickl et al. 2013; Karelina and Etkina 2007; Finkelstein et al. 2005; Kontro et al. 2018).

To be able to categorize our approaches of using AR technology and smartglasses in the context of lab courses, which will be discussed in detail in the following section, there is a need for a generalized view of what can be learned during a lab course. Because of the variety of learning environments concerning this topic, it is hard to cover all aspects of lab courses without losing the view on the special features of each design approach. However, the curriculum goals formulated in AAPT's associated recommendations (AAPT 2014) are precise enough to provide a certain base structure to design a lab course, and they are abstract enough to enable different institutions to implement them with respect to their available resources, student population (major and nonmajor), or specific pedagogical intentions. That means, these goals are a universal tool to compare different lab course arrangements according to the key aspects of their learning intentions, because several learning outcomes, that are claimed to be reached by students during lab courses, are being described. These include constructing knowledge, modeling, designing experiments, developing technical and practical laboratory skills, analyzing and visualizing data, and communicating physics. It is obvious that not all of them can be addressed during one single lab course.

However, these recommendations picture some general aspects on a macro level without highlighting their connection or the mutual conditions. An even more student-orientated perspective is needed to operationalize disjoint areas of activities that represent self-contained parts of the proceedings during a lab course, e.g., planning, performing, and analyzing the experiment.

The structure model for experimental competencies according to Schreiber et al. (2012) describes fundamental competencies and skills students might foster during laboratory courses. It is almost congruent to AAPT's recommendations, but it follows a certain schedule of a laboratory course beginning with the preparation and ending with the interpretation of the results (Table 1). Therefore, it is useful to operationalize each step taken during a laboratory activity without demanding the compliance of the plot. Hence, these disjoint steps may be used to describe the key aspects of different design approaches and to characterize them.

Table 1 Model of the experimental competencies according to Schreiber et al. (2012) as found in Theyßen et al. (2014)

Preparation	**Performance**	**Data Analysis**
Clarify a question	Collect devices	Prepare data for processing
Develop a question	Assemble the experimental setup	Process data
Express expectations	Perform measurements	Interpret the results
Phrase a hypothesis	Document measurements	
Create an experimental design	Cope with problems and errors	

To make our wearable approach connective to the variety of lab courses, an analysis of its specifications concerning learning experiences has to be done. To do so, smartglasses are being described as a multimedia learning tool and its characteristics are investigated under the perspective of cognitive science.

Although we present the possibilities of smartglasses with respect to a general use in lab courses, we also want to phrase a concrete way to realize these ideas. In order to show that the technology is ready to be implemented in higher educational settings, we present the adaptation of a traditional experiment dealing with the thermal conductivity of metal rods as a first step to illustrate our approach.

1.2 AR Learning Environments and Smartglasses

During the last decade the development of modern digital media, such as smartphones and tablet computers, have triggered an experimental revolution in STEM education. These devices include numerous sensors covering different physical quantities and have been successfully established as portable minilabs for use in schools and in university courses in the last years. Today, integrated sensors allow to perform experiments in almost all fields of physics, e.g., mechanics, optics, acoustics, or even nuclear physics (cf., e.g., Vogt et al. 2011; Schwarz et al. 2013; Kuhn et al. 2014; Klein et al. 2014; Kuhn 2014; Hochberg et al. 2014; Klein et al. 2015; Hochberg et al. 2018). The capabilities of these devices can even be extended if external sensors, e.g., gas sensors, are used to perform measurements. Regarding the precision of the experimental measurements, these smart media devices are certainly able to keep up with classical measurement devices used in teaching scenarios at school and university. Their high availability, however, is a huge advantage, which opens new possibilities for, e.g., informal learning settings and ubiquitous learning (cf. Johnson et al. 2014). In the last years, the developments concerning virtual reality (VR) and augmented reality (AR) have complemented these technologies and opened the doors to new worlds providing different levels of immersion of the user.

While VR totally immerses a user into a computer-generated environment, which can simulate either a lifelike experience or any other imaginary world, AR aims to enrich the real surroundings with digital enhancements, so-called augmentations. In the virtuality continuum introduced by Milgram and Kishino (1994), which spans from purely virtual environments on one end to the real world without any augmentations on the other, AR therefore ranges somewhere in the middle, combining reality and virtual elements. Thus, also the term mixed reality (MR) is sometimes used equivalently referring to AR scenarios. Following the definition of Azuma (1997), which is mostly used in the AR community, a system creates an AR experience, if three characteristics are fulfilled: It combines real and virtual, it is interactive in real-time and registered in 3D, the latter referring to the correct alignment of real and virtual coordinate systems, to create the illusion of a consistent placement of the virtual objects in real space.

Both technologies, VR and AR, address both channels of information processing, the visual via different display types and the auditive via loudspeakers. A VR experience is usually created using head-mounted displays (HMD) as, e.g., in gaming devices like Oculus Rift or HTV Vive but also simply with a smartphone inserted into a cardboard. There exist several ways to generate a more or less immersive AR experience.

One possibility is to augment the live video stream on any display, e.g., a smartphone or tablet computer, in a way that changes the content itself, like in the Google Translate app (cf. Google 2018), where text is replaced by the desired translation in real-time, or that adds digital images in the correct 3D perspective, like in the IKEA Place app (cf. IKEA 2018). This creates the illusion of the digital object actually being placed into the real world. Such a realization of AR using external displays, however, only augments the digital live video feed, not reality itself, creating a sharp “mixed reality boundary” Benford et al. (1998) at the borders of the device’s display.

A more immersive realization of AR by Bimber and Raskar (2005) uses projectors to create so-called spatial AR. In this approach digital augmentations are projected onto real-world objects themselves. The quality of this approach strongly depends on the objects that are augmented; the structure and the color of the object’s surface as well as the lightning of the surroundings play an important role. The huge advantage of this technique is the fact that the augmentations can be observed with the naked eye, without the need of any additional device. Moreover, this also means that all persons observing the augmented object may also simultaneously look at the projected augmentation. However, if the position of the projector is fixed, while users are allowed to move freely, the augmentations can only be optimized for a certain class of view angles. Furthermore, especially if interactions between the users and the objects come into play, occlusion can be an issue, as the light coming from the projector might partly be blocked, e.g., by the user’s head or hands.

Another approach is to use the technique of HMDs. So-called video-see-through systems use HMDs—as in VR applications. However, in this case the real-time video feed of a head-mounted stereo camera is presented. This video can then simply be augmented, as in the case of the AR version with handheld displays. In this setting one has to deal with a constant parallax introduced to the fact of the camera angle being slightly different form the person's view angle. Optical-see-through setups, on the other hand, use transparent displays, which allow to see the real environment while wearing the HMDs; in this case the displays only show the virtual augmentations as an overlay to the real world. This technology is used in smartglasses like Microsoft HoloLens. Both techniques require the exact knowledge of the position of the head of the users as well as the position of the objects that should be augmented. These positions can be acquired via tracking with sensors, e.g., optical cameras or depth sensors.

A downside of today's smartglass technology is the still limited field of view. Indeed it could be shown in a recent study by Baumeister et al. (2017) that using an AR experience with a limited field of view can increase the extraneous cognitive load (CL) of the learner. This might suggest that projector-based spatial AR despite its technical difficulties could be more beneficial with respect to the avoidance of extraneous CL as AR based on HMDs. A limited field of view, however, is an issue especially for large-scale augmentations, as the angular diameter is large in this case; with regard to standard laboratory tabletop setups, this should only be a minor limitation that will be overcome in the next generation of smartglasses. Moreover, talking about learning scenarios in science laboratories for undergraduate STEM courses, one has to deal with partly complex setups of various different devices, which have to be plugged together by the students in order to perform experiments. In such a setting projection-based AR comes up against limiting factors: the different surfaces of the used devices can hardly all be augmented with the same quality due to their different distances to the projector, which moreover possibly will change during the process of experimenting. Furthermore the angle under which the setup is viewed by the students may change during the experiment and handling the devices will constantly lead to occlusion problems.

In recent years, modern AR technologies have quickly made progress (cf. Sandor et al. 2015; Schmalstieg and Höllerer 2016; Hockett and Ingleby 2016) and finally also have entered the field of education (cf. Billinghurst and Duenser 2012; Santos et al. 2014; Bacca et al. 2014). However, the results regarding learning effectiveness of such scenarios at the moment do not yield a coherent picture. While some studies report AR was enhancing motivation of the participants (Jara et al. 2011; Di Serio et al. 2013; Bujak et al. 2013; Chang et al. 2014; Kuhn et al. 2016), their curiosity or the positive attitude to the experimental topic (Kuhn et al. 2016; Akçayır et al. 2016), or it was helping to authentically discover the environment (Dede 2009) and to observe processes, which cannot be seen with the naked eye (Sotiriou and Bogner 2008; Wu et al. 2013), others state that users often have to cope with technical problems using this technology and rate it as complicated (Lin et al. 2011; Wu et al. 2013; Akçayır et al. 2016). In any case, according to Muñoz-Cristóbal et al. (2015), additional introductory lessons are indispensable to create benefits from the use of AR, but still, if user experience and usability are insufficient and the user environment is not designed in an appealing way, learning with AR technologies will inevitably fail (cf. Squire and Jan 2007).

Thus, it is crucial to make an effort to derive design principles for AR learning environments, which can be deduced from multimedia learning theories. Therefore, we present theoretical foundations from selected psychological topics and their implications for the use of AR with smartglasses, revealing advantages and limitations for the learner's experiences. Furthermore, we deduce basic design principles for the creation of a smartglass learning environment and reconsider the experimental competencies and skills under the perspective of multimedia cognitive support by smartglasses in order to highlight those subdimensions of laboratory action that might be fostered.

2 Theoretical Background

Empirically validated theoretical foundations for the process of learning with multimedia environments have been successfully established during the last decades. In this section, we will give a recap of the current theories and discuss their implications. These, however, have been developed and tested using classical multimedia learning environments that combine different representations like written text, spoken words, videos, and animations on one or more screens. Today augmented reality (AR) technology is able to combine virtual augmentations with the real world into one multisensory immersive experience, e.g., with the help of smartglasses, which address the visual as well as the auditory channel. This allows for, e.g., digital real-world annotations, interaction with virtual characters, and instant feedback to real-world actions. Today it is not clear whether all classical multimedia design principles can be directly transferred to AR scenarios; however, several of these principles seem to be of special interest in such settings, as significant improvements can be expected here, as compared to traditional multimedia settings, which have much more restrictions to obey the respective principles.

2.1 Learning with Media

Knowledge about the architecture of human cognitive structures is crucial for the deeper understanding of the organization of cognitive processes. Cognitive load theory (CLT) according to Sweller (1999) is based on this knowledge and integrates its constraints to deduce instructional design principles. A huge restriction of human cognitive capabilities is the fact that working memory capacity is severely limited as, e.g., comparison or manipulation is not possible with more than two to four items at once (cf. Paas and Sweller 2014). Therefore, it is crucial to ensure that this limitation does not hinder learning processes by creating instructional guidance taking into account human cognitive structures and thus allowing for an optimal use of working memory abilities.

CLT provides such a framework for the design of instructional material. It distinguishes three different types of CL which are additive, while total CL is bounded from above due to limited memory capacity. The first type, intrinsic CL, is due to the intrinsic complexity of a (learning) task and cannot be modified without altering the task itself. Extraneous CL on the contrary is caused by inappropriate instructional material and is not connected to the process of learning. Instead, it emerges if unsuitable learning environments, ignoring cognitive limitations and inhibiting a strong focus on the learning task itself, are presented. This is the case, if, e.g., distractions or irrelevant information are present (redundancy effect), if the learner's attention has to be split between two spatially or temporally distinct relevant sources of information (split-attention effect), or if information is only presented in one mode, e.g., the visual mode (modality effect). The last type, the so-called germane CL, is directly connected to the learning process itself. It might be understood as effective CL, which stems from meaningful learning and active construction and automation of schemata in the long-term memory. As both extraneous and germane CL depend on the presentation of the learning contents and since the total cognitive capacities are limited, according to CLT the aim in constructing instructional material is to reduce extraneous CL while simultaneously increasing germane CL. However, it is important to tailor the materials especially for the target group, as the split-attention effect as well as the modality effect may be lost in the case of more experienced learners or experts (expertise reversal effect), which can be explained with the help of the redundancy effect: For persons with a higher expertise parts of the information still relevant for novices become self-evident. In this case, a physical integration of the information or a transfer to a different modality has no positive effect as it opposes the self-filtering capabilities of the experienced learner.

Augmented cognitive load theory (aCLT) (cf. Huk and Ludwigs 2009) goes one step further and also includes affective variables into the framework of CLT. It assumes that a reduction of extraneous CL might not inevitably lead to an increase of germane CL, as free parts of the learners' working memory might not automatically be used in favor of germane CL. Instead, germane CL might change, even if extraneous and intrinsic CL are held constant. In fact, according to aCLT, cognitive as well as affective variables are able to influence the level of germane CL. Indeed, both complement each other, as cognitive assistance aims to support the construction of mental schemata in an active learning process, while affective assistance is able to increase the situational interest of the learners. It could be shown by Huk and Ludwigs (2009) that interventions combining both cognitive and affective support lead to a better understanding compared to interventions in which only one type of support is provided. This means that the influence of cognitive and affective variables on learning performance are additive and thus both should be included in the design of instructional material.

While CLT establishes a framework for the process of learning in general, Cognitive theory of multimedia learning (CTML) according to Mayer (2014b) focuses on the special case of learning with multimedia environments, i.e., learning scenarios combining different representations and modalities. In many aspects CTML and CLT effectively address similar issues and lead, as we will see, to paralleling suggestions for improving the process of learning.

According to the multimedia principle by Mayer (2014b), learning from words and pictures is more effective than learning from words alone. Taking this as a starting point, CTML tries to establish a set of rules which allow to follow and extend the multimedia principle while simultaneously taking into account human cognitive structure to ensure an optimal learning effect.

CTML is based on three main assumptions, deduced from cognitive science (cf. Mayer 2014b): First, human information processing is split into two independent channels – the visual/pictorial channel and the auditory/verbal channel. This is directly linked to the second assumption stating that both of these channels have a limited capacity. These two assumptions resemble aspects of CLT, and find their counterpart in the limitation of working memory and the modality principle. The third assumption postulates an active processing of humans, i.e., the construction of active mental representations by the learner. This expresses the ability to create a coherent picture of their experiences through active attention and further processing of incoming information, including organization and integration with established concepts from long-tern memory.

Both channels are assumed to have sensory inputs, which are able to read information, e.g., in terms of different multimedia representations. In working memory information of both channels is actively selected and organized to create a verbal and a pictorial model, respectively. However, in this process, information of the two channels may interact with each other. In the end, both models as well as prior knowledge from long-term memory are integrated into a coherent full mental model.

In addition to this framework cognitive-affective theory of learning with media (CATLM) includes further assumptions (cf. Moreno 2005; Moreno and Mayer 2007): affective variables, like motivation and interest, are also relevant during learning processes as they increase cognitive engagement and thus enhance learning. These variables might therefore actively change the process of information selection from the sensory memory as well as the process of organizing the different inputs in the working memory. Affective components are fed from the long-term memory, which is assumed to be split into a semantic and an episodic memory which correspond to the two channels, respectively. Moreover, CATLM also includes tactile, olfactory, and gustatory aspects of the sensory memory, which are assumed to be strongly linked to the episodic memory and thus also influence the active process of learning. According to Moreno and Mayer (2007) this might especially be of interest in the context of interactive learning environments, which is always the case in laboratory settings. Besides this, CATLM also includes metacognitive factors which mediate learning through self-regulation of the learners, as well as differences in pre-knowledge and abilities between different learners, which also may have an impact on the learning efficiency of a specific learning environment for the individuals.

2.2 Implications of the Multimedia Design Principles

As a result of the preceding theories, there is a need to manage the different forms of CL during a learning situation. Hence, the design of the learning environment and the instructional material are the main aspects to take care of. As mentioned before, smartglasses with AR technology are able to address both the visual and auditory channel (cf. also Sect. 1.2). Thus, all design principles for controlling and reducing CL derived from the cognitive theories (CLT, CTML, etc.; cf. Sect. 2.1) can be applied. A summary of the selection of these principles that fit the possibilities of smartglasses is presented in the next paragraphs.

According to the theories above, the outcomes of a learning situation are determined by the specifications of human cognitive architecture. In particular, the limitations of working memory led to a boundary condition for the integration of novel information received from a multimedia message. If the content of a learning material exceeds these capacities, it leads to a cognitive overload situation and the learner has no more resources to process the essential material and to create learning outcomes.

Mayer and Fiorella (2014) derived five ways to manage cognitive resources and to guide the learner's cognitive processing, to avoid overload situations. Focusing on the reduction of extraneous load, they demand (cf. Mayer and Fiorella 2014) the elimination of extraneous load (coherence principle), the insertion of signals that emphasizes the essential material (signaling principle), the elimination of redundant printed text (redundancy principle), the positioning of printed text to corresponding parts of graphics (spatial contiguity principle) which according to Fujimoto et al. (2012) simultaneously facilitates memorization, and the elimination of the need to hold essential material in memory for a longer time (temporal contiguity principle). Notably, as mentioned before, the implications from spatial and temporal contiguity coincide with conclusions drawn from the split-attention principle from CLT (cf. Sect. 2.1), and also the redundancy principle has already been deduced from CLT.

These five principles are also reflected in CATLM and have been cast into the ten design principles for learning in high-tech and multimedia learning environments by Moreno (2006), which present basic ideas for the arrangement and presentation of multimedia messages in a learning environment.

Complementary to the five-point approach of Mayer and Fiorella (2014) to avoid or manage cognitive overload, Moreno describes the chances of using multimedia to foster the learning process. Those ten design principles are shown in Table 2.[1]

[1]Further information about the theoretical rationale can be found in the original publica tion by Moreno (2006).

Table 2 Ten design principles for a multimedia learning environment by Moreno (2006)

Principle	Description
Modality	Students learn better from words and graphics when words are spoken rather than printed
Verbal redundancy	Students learn better from graphics and narration than from graphics and redundant narration and text
Spatial contiguity	Students learn better when multiple sources of visual information are integrated rather than separated
Temporal contiguity	Students learn better with concurrent rather than successive corresponding words and graphics
Coherence	Students learn better when extraneous material is excluded rather than included in a lesson
Multimedia	Students learn better from words and graphics than from words alone
Personalization	Students learn better when explanations are personalized rather than non-personalized
Guidance	Novice students learn better when given principle-based explanations than they do when asked to infer principles by themselves
Interactivity	Students learn better by manipulating the materials rather than by passively observing others manipulate the materials
Reflection	Students learn better when given opportunities to reflect during the meaning-making process

2.2.1 Implications for the Design of AR Environments for Smartglasses

Previous empirical research on multimedia principles in the context of learning situations focused on a clean study design with special instruction materials to investigate a single or a disjoint selection of the principles from Table 2. In addition, the term multimedia was used in its simplest form: materials containing texts, pictures, and narrations that can be explicitly matched to a cognitive channel (cf. Moreno 2006).

Using multimedia in combination with AR and smartglasses, however, means to be able to add information to your field of view, like an overlay on reality. Any multimedia element (e.g., text, pictures, and videos) that can be created and displayed on a 2D screen can also be displayed on a smartglasses' screens. Hence, we can extend the use of multimedia from static or separated screens to the field of view and carry this information with us. Furthermore, we can use 3D content in a real-world environment that is not an illustration or copy of reality. In addition, we can use integrated speakers to provide sound and narration such that a smartglass really can deliver a multimedia message addressing the dual channel perception system of human's cognition, resulting in the application of Moreno's multimedia and modality principles (Table 2; cf. Moreno 2006).

The technology also allows the interaction between "smart systems," i.e., the transfer of real-time data from objects in the real world to the smartglass, to process this information and to provide corresponding content to the learning environment respecting both the visual and the auditory channels. In particular, the use of technology means that instructors do not just have to create a piece of paper with instructions; they rather have to design the whole learning environment containing visualizations, their arrangement, the structure of the action, and the user's interaction with both the technical device and the learning objective.

In fact, instructors have to create and organize different plots of multimedia messages that will be presented to the learner via the smartglass. Vice versa, this effort to create the whole situation gives the opportunity to control the basic boundary conditions of multimedia messages, like the coherence of the presented material or the avoidance of verbal redundancy.

With the use of multimedia elements like text and pictures, graphics, videos, narration, etc., we add information sources that address different channels and may be seen as much extraneous material at a first glance (cf. Mayer 2014a, p. 280). But the way these materials are arranged in the learning situation may change their effect on the learner's perception completely. The most important aspect is to focus on the essential parts of the material and to prevent an overload of the learner's cognitive capacity. This load management contains the design of material with respect to the consequences for the processing in working memory and the interdependency between material and learner, resulting in the three forms of CL.

Concerning the use of smartglasses in the context of laboratory courses, we have to confront the situation that nearly all of these principles must be considered to avoid cognitive overload. Hence, we use these principles as a guideline to design the interplay between augmented content and real-ity (i.e., mixed reality) to create a learning scenario that fosters multimedia learning.

Because of the technological possibilities of smartglasses we are able to integrate texts, pictures, narration, and different static and dynamic representational forms of experimental data (like raw values, tables, graphs, animations) in real-time next to the corresponding object in the real world. This ability of visualizing experimental processes happening at the object itself picks up the ideas of preventing the split-attention effect. Even in an environment bigger than just a screen or a piece of paper, AR technology guarantees the connection between objects and the corresponding information, like experimental data observed at this object. Thus, we extend the spatial contiguity principle from a 2D setting into a 3D environment. As a first approximation, spatial integration of information yields the connection between the object as a part of the experimental setup, i.e., the physical reality and the representation of the data as a tangible visualization of a physical quantity. Because the data is visualized in real-time, every change of variables and parameters of the experimental setup has corresponding consequences for the values and the representations. This feedback loop between reality and augmented information happens with such a high refresh rate that changes appear in a continuous and dynamic way rather than in discrete steps. Hence, this lack of delay between action and visualization means that temporal contiguity is reached in order to connect observable information to conceptual ideas.

As a matter of fact, in AR scenarios reality itself also comes in as a big additional source of information, not all parts of which are relevant for the current task, e.g., in a laboratory. This might in general also lead to overload situations in such a setting. Following the signaling principle and yielding cues and signals as well as highlighting or marking objects or regions in reality is also possible with such technologies and can be used either to smoothly nudge the learner into the right direction or to immediately draw the attention to important issues, which in the case of laboratory settings might even be relevant for security issues. For example, if a component reaches a critical temperature, a signal highlighting this component as "dangerous when touched" can be visualized. In general, objects can be highlighted and connected to spoken or visualized instruction. This guidance may help learners to focus on relevant components and to organize and structure their experimental investigations. Therefore, this guiding schema gives an example of how to go through the experiment providing learners with a predesigned plot they may follow (guidance principle; cf. Table 2).

A well-designed user interface allows to control structure and pace of the action according to the learner's own capabilities. One possibility to control the multimedia messages is to simply use one's gaze. If learners want to see the spatial connected information of an object, they have to look at this object actively, when and how often they want to. Hence, learners obtain enough time (and space!) to reflect the multimedia message, i.e., what can be seen and what can be heard, and to process the inherent essential information. This reflection principle is available due to many degrees of freedom concerning the learner's interactivity. Latter is also the reason for having a personalized learning situation. What is presented in the augmented information is a consequence of the learner's action. If fundamental parameters are changed, for example, by manipulating the experimental setup, the learner gets the information of the outcomes via representations of the physical quantities. Hence, a relationship between action and outcome can be established without any spatial or temporal delay. This allows learners to interact with the learning objective in a personalized way, because changes and consequences are produced by their own action and organized in their self-chosen pace. The real-time feedback provided by the multimedia messages reduces the need to hold the information of their (complex) interaction in their working memory over a longer period of time and enables the reflection of the interplay between action and outcomes. Providing signals and cues supports this reflection processes by giving hints for the relevant structures and information.

To sum up, the use of smartglasses in combination with AR technology enables instructors to design a multimedia learning environment that includes basic design principles to manage CL and therefore a cognitive support for the learner. Designing such an environment requires to deal with cognitive psychology, instructional design, and the reflection of the user interface. However, further research has to be done to find out whether it is definitely allowed to transfer the foundations of 2D multimedia learning theories to such a complex and interdependent conglomerate of multimedia elements in 3D environments.

2.2.2 Implications for Laboratory Learning Environments

In Sect. 1.2, we claimed that using smartglasses as a multimedia learning tool may support different aspects of competencies and skills necessary for experimental actions. For the construction of knowledge, the (personal) observation and interpretative analysis of measurement data is essential. Both the spatial and the temporal contiguity principle enable students to connect the observation of data to the observation of the experimental setup in real-time and with respect to their own pace. There is no significant delay between the occurrence and detection of data—students immediately get feedback about the status of the experiment. Because this data is a direct result from their own action (interactivity principle), they may integrate this information better, because the action was founded on their own thoughts and questions concerning the learning objective. Moreover, in such scenarios, affective motivational factors might play an important role, as also the other sensory inputs, like the tactile input, as included in CATLM may be important here, which in combination with self-performed actions in a laboratory could incorporate a strong link to the episodic memory and increase the element interactivity.

Concerning the competency model of Schreiber et al. (cf. Table 1), AR works as a feedback system by integrating the "interpretation of results" into the "performance of measurements" leading to an interplay with "phrase a hypothesis." That means, while students have the opportunity to think about the (real-time) data, they interpret the results of their experimental action immediately. This enables them to change their experimental action in order to investigate these interpretations with regard to their hypotheses. Reversed, they may change their hypotheses because of their interpretations leading to the need of changing the experimental action itself.

The key aspect of this feedback system is the visualization of real-time data. Aside from being able to process the raw information, such that the visualizations will appear next to the corresponding real object, the data can be prepared in almost any kind of representation and signals or cues can be added. In fact, the visual attention of the learner can be guided by highlighting objects or parts of them in order to simplify the scenery and structure the learning process. This supporting system to filter relevant information may help students to focus on main parts of the experiment, enabling them to focus on the interpretation and conclusions of the data. The variety of possible representations reaches from raw values to complex graphs, so that a scientifically accurate visualization of data is guaranteed and there is still an educational scope to reduce the complexity of information in order to match the learner's cognitive performance level. Such a broad variety enables instructors to individualize the learning situation in such a subtle way that the structure and plot of the action during the experimental process satisfies the educational need of the learner. Eventually, with the help of the prepared graphs and the real-time data, the learner gets the possibility to think about the status of the experiment during the interaction without losing any degree of freedom concerning the control of the pace and the interaction with both the technical device and the setup itself.

To sum up, the broad variety of visualization concepts and the connectivity to the learner's performance level may particularly result in the support of the knowledge construction while performing the experiment and analyzing the data. Instead of waiting for the analysis by hand, the results of the interaction can be made a subject of discussion in real-time. Especially with respect to the contiguity and signaling principles, the learner is guided to maximize the learning outcomes of this real-time discussion and interpretation due to a support of the cognitive processing of novel information. Respecting these multimedia principles may result in a well-founded feedback design of the learning environment.

3 Toward a holo.lab

Based on the design principles deduced from cognitive theories, as presented in the preceding section, in this section we will explain how we want to benefit from the use of smartglasses in laboratory learning scenarios in our holo.lab approach.

3.1 Smartglasses as Experimental Tools

If standard smart media such as smartphones or tablet computers are used for (AR) learning environments, all design principles of multimedia learning can hardly be obeyed. Besides their high computational power and various internal sensors, the nature of devices like smartphones or tablet computers is simply that of an external handheld display. It can be assumed that this fact gives rise to a conflict with the contiguity principles. In the case of a laboratory activity, this means that if a person is working with an apparatus while further information, e.g., measurement data or explanations, is presented on an external monitor, it is simply not possible to observe both the apparatus and the screen at the same time. The user might then simply look back and forth, thereby trying to integrate the spatial discontiguity or first focus on one of the two sources of information, before turning to the other, thus integrating the data temporally; this would inevitably lead to a higher level of CL. Moreover, such a handheld device at least partly inhibits a just-in-time interaction with the experiment, since at least one hand cannot be used to manipulate the apparatus.

One can suspect that technically spatial AR using projectors and AR via smartglasses both would overcome the discontiguity problems with handheld devices as we have seen in Sect. 1.2. Despite the drawbacks associated with the limited field of view (cf. Baumeister et al. 2017), to ensure a perception of the environment which is as natural as possible, in the settings described in the following sections, we thus focus on the realization of AR content with smartglasses. In a lab setting students may then see the experimental apparatus and also their collaborators face to face and benefit from augmentations at the same time. Furthermore, in such a setting also additional augmentations, which are not fixed to surfaces of real objects, can be included, which can be crucial for inserting cues, informatory or explanatory tags, but also data visualization.

3.1.1 Visualizing the Invisible

As we have seen in the last section, smartglasses are ideally suited to realize AR learning environments, which obey basic multimedia design principles. However, when it comes to physical experiments, there exists another huge advantage of this technology, namely that of helping to visualize the invisible. While human senses are of great help when performing various experiments, e.g., in acoustics or optics, at the same time many abstract physical quantities, like energy, heat, or voltage and current, are not covered by human perception. Nevertheless, fundamental physical concepts are based on such abstract quantities, for which an intuitive understanding often is lacking. This intuition deficit might be reduced, if a learner would be enabled to directly interact with the quantity under discussion, allowing to establish a feedback loop and thus a reflection of the behavior of the physical subject.

Indeed, the gap in human perception can be overcome with the help of AR technologies, which also allow for true interactivity. Today digital sensors are available for a huge number of different physical quantities, which otherwise are inaccessible to human perception, like temperature, voltage, and electrical current or electromagnetic fields. As smartglass technology is able to completely cover the virtuality continuum, leading to a true immersive virtually augmented world experience for the users, it is possible to embed virtual objects into the real environment. In such a digitally enhanced surrounding, virtual and real objects do not only co-exist, but moreover are also able to interact with each other in real-time. Hence, digital sensor data from external sensors can be used to create augmentations which are integrated seamlessly into the environment and enrich human perception with further senses.

Therefore, we use smartglasses to merge human perception of reality with digitally visualized sensor data directly in the user's field of view, thus obeying spatial and temporal contiguity. We realize this by transferring sensor data to the visual sense, which can be achieved by transforming it into different representations like various types of diagrams, symbols, or false-color representations. A learning scenario including such a technology, we call a holo.lab. An AR learning experience like this is finally able to make the invisible visible and the not observable apparent.

In general there exist two possibilities to realize real-world annotation, i.e., to present object-related data in an AR scenario. The first is to simply show a representation of the data in direct neighborhood to the real object. This could for example simply be to display the numerical value of the voltage over light bulb in some electrical circuit. In this case also other representations, e.g., all sorts of diagrams, may similarly be used. Such an augmentation in general cannot be realized with a projector-based scenario, as a corresponding surface for such a representation would have to be present in this case. In the second approach the object itself is augmented. An example for this technique is the augmentation of an object with a false-color representation of its own temperature distribution such that the color of each point of the object represents the corresponding temperature of the physical object at this point, which we will discuss in detail in the following section.

3.1.2 Using HoloLens in an Experimental Setup

In our laboratories, we use HoloLens technology to create AR learning environments as a holo.lab scenario (cf. Strzys et al. 2018). The virtual objects, which are shown on the HMDs of HoloLens—the so-called holograms—can be used to annotate real objects and to show diagrams and other representations but also for a complete augmented overlay of real objects with new digital texture. Such applications are only possible, as HoloLens itself guarantees a very high quality level of spatial registration of the virtual objects in real space and an elaborate tracking of its surroundings. Therefore, if a user has placed a hologram somewhere in real space, he is free to move around and look at it from different points of view. Even if one leaves the room one will find the virtual object still exactly at the initial position when re-entering the room.

To attach the holograms to real-world objects also an object tracking has to be implemented. The easiest way to achieve this is via visual markers fixed on the real objects. Since these markers can be tracked using the cameras of HoloLens, the positioning of the virtual content can then just be achieved relative to the marker coordinates. This is also possible for more than one HoloLens at the same time, as every HoloLens performs its own marker tracking and displays the corresponding AR objects independently.

There are many ways to interact with HoloLens and thus to interact with the virtual augmentations. All holograms can be chosen with the so-called gaze point, a cursor that can be moved with the user's gaze. As soon as the gaze point meets a hologram ready for selection, it will be highlighted. It may then be selected using the so-called air-tap gesture. This hand gesture is simply an analogue of clicking on a mouse or a touch pad and can be performed by tapping with the forefinger at any point in the gesture frame. This frame is a specific region located within easy reach of a person's hands, limiting the operational area of the gesture recognition of HoloLens. Besides gestures, there exist two more possibilities to interact with HoloLens: One is to use a clicker, a small handheld device with a button that allows to select a highlighted hologram; the other is speech recognition which allows a totally hands-free interaction.

Since lab work often is teamwork, a holo.lab scenario moreover has to be designed in a way that allows collaboration of several persons, all of them interacting with the experimental apparatus as well as with the AR content, especially with the sensor data. Depending on the conditions one possibility is to ensure that all users attending the experiment are able to see and to work with the same representations which allows to discuss the measurement data on a common basis of virtual annotations and evaluations presented in their shared MR experience. The other possibility would be to allow for individual representations, either chosen on purpose by the single user, or suggested automatically by the system based on the evaluation of the user's behavior. This individualized scenario would follow the personalization principle (cf. Table 2) and should effectively meet the special needs of different learning types. In an ideal version all these possibilities should be included in a holo.lab realization.

3.2 holo.lab for Heat Conduction

As a first holo.lab example, we have implemented an AR version of a standard experiment on heat conduction in metals for an introductory STEM laboratory course in thermodynamics (cf. Strzys et al. 2017, 2018). The experiment consists of different metal rods, which are electrically heated at one end while simultaneously cooled at the other end. Each rod exists in two versions, an uninsulated one and a second one with a PVC insulation layer (cf. Fig. 1a, b). An infrared (IR) camera is used to access the temperature data along the rod, which is then passed to the students' HoloLens. The educational potential of IR cameras and their ability of visualizing thermal phenomena on the level of primary school up to university physics (cf., e.g., Vollmer et al. 2001; Möllmann and Vollmer 2007; Vollmer and Möllmann 2013; Haglund et al. 2016a, b; Nordine and Weßnigk 2016; Palmerius and Schönborn 2016) can be merged with the benefit of spatial and temporal contiguity in a holo.lab setting. To achieve this, we project the real measurement data of the IR camera in real time as a HoloLens hologram directly onto the rod using a false-color representation (cf. Fig. 1c, d). As these augmentations are mutually 3D and registered in real space, students can observe the heat flux through the rod from all angles without the problem of occlusion. Additionally, other augmented representations, a temperature graph and numerical temperature values, can also be switched on and off during the experiment using virtual buttons (cf. white squares at the right end of the rod in Fig. 1c, d). This allows for virtual interactivity and enables the learners to choose their own preferred representation which according to the personalization principle also prevents overload situations. However, representations used by all of the learners can also be included in the discussions among the group members, creating new possibilities for collaboration. Additionally, the current temperature data can also be exported to CSV file at any time for later traditional analysis.

With this holo.lab setup, a just-in-time evaluation of the physical process in this experiment can be achieved: all stages of the heating procedure, beginning with the initial state, in which the rod uniformly is at room temperature, and ending with the formation of a stationary state with a hot end, a cold end, and a temperature distribution depending on the insulation conditions of the rod, can be observed and evaluated in real-time, using all three representations of the sensor data. As we have discussed in Sect. 2.2, this is the key to establishing a feedback system. This feedback can be used to critically reflect on the performed procedures as well as the results of the measurements, since in such a scenario the time-consuming

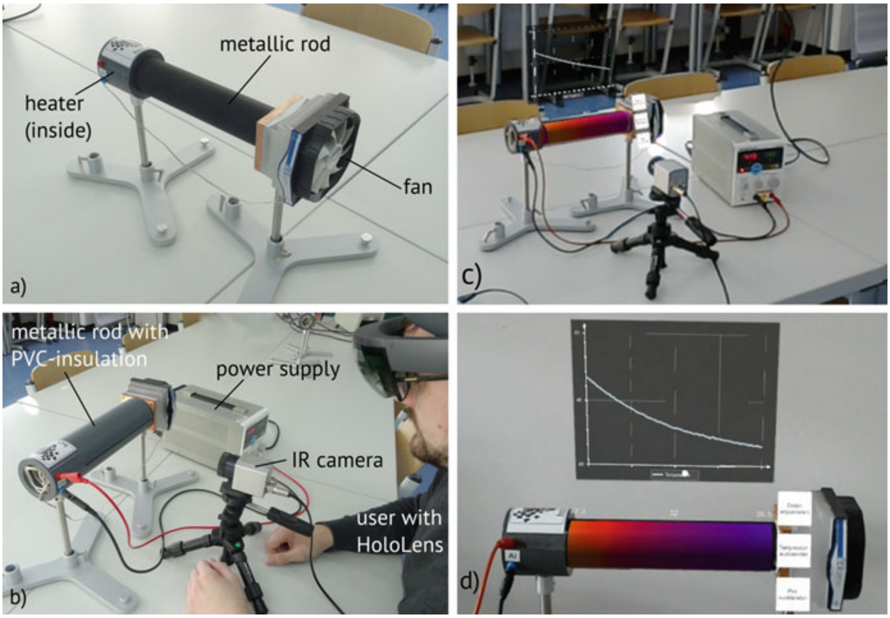

Fig. 1 (**a**) Experimental setup (uninsulated rod); (**b**) experimental setup (rod with PVC insulation) and user wearing a HoloLens; (**c**) holo.lab setup (uninsulated rod) with AR experience; augmented representations: false-color representation of temperature along the rod, numerical values at three points above the rod, temperature graph; (**d**) detailed view of the augmentations, three buttons at the right: "Export Data," "Hide Temperature," and "Hide Plot"

procedure of processing the data and casting it into the appropriate representation is taken care of by the learning environment itself. This frees cognitive resources of the students, allows them to pause and reflect on the observations, and thus fosters their learning progress according to the reflection principle. Moreover, the virtual content might also provide representations of theoretical predictions and thereby enables a direct comparison of the experimental outcome with the idealizations of theory. As both of them possibly might not coincide with the students' own expectations, such feedback can trigger cognitive activity and might lead to a critical reexamination of concepts, to reduce cognitive dissonances (cf. Munnerley et al. 2012).

As our holo.lab setting is completely smartglass-based, students still have their hands free to interact with the physical apparatus and simultaneously focus on the system's response via AR informations in their field of view. Therefore, students' individual expectations concerning the outcome of an experiment resulting from personal preconcepts as well as from theoretical implications can also start an experimental feedback loop including new experimental actions and reactions due to critical reflection to achieve verification, which according to the interactivity principle enhances learning possibilities and might eventually even trigger a conceptual change (cf. Brown and Hammer 2013).

To evaluate the learning efficiency of our holo.lab approach, we conducted a first pilot study with a treatment and a control group (cf. Strzys et al. 2018), which indeed showed a positive effect on the conceptual understanding of students using the described setup for the thermal conduction experiment. While the control group performed the experiment with a traditional setup, using a handheld IR camera and a PC, which excludes a just-in-time feedback loop as well as real object annotation and augmentation, the treatment group used the holo.lab setting. We compared students' performance in a concept test on heat and temperature in a pre- and post-test design and found a small positive effect of the holo.lab setting (effect size Cohen's $d = 0.43$), indicating an improvement of the understanding of the underlying physical concepts. As in this experiment the theory-experiment interactions are relatively limited, one may expect that complex experiments could benefit even more from AR technology.

This first realization of a holo.lab scenario mainly focuses on the idea of real-world augmentation to overcome the limitations introduced by the split-attention effect by avoiding discontiguities and on establishing the possibility of a real-time feedback loop with regard to theoretical implications as well as experimental actions. However, the inclusion of guidance elements via cues, hints, and explanations could also be included in a straightforward way. Moreover, as true experimental interactions are rather limited in this relatively static setup, more engaging layouts combining more components would yield a plenty of possibilities for broad interactivity. This could also be embedded into a problem task, if, for example, different materials should be combined in a way to ensure a heat transfer as fast as possible, or different insulation strategies should be compared to achieve minimal energy loss. Such an affective support via goal-based scenarios would finally also enhance learning according to CATLM (cf. Moreno 2005; Moreno and Mayer 2007; Huk and Ludwigs 2009).

4 Discussion and Outlook

The positive results of our first evaluations of the conceptual understanding of students support the assumptions concerning the beneficial value of AR scenarios in laboratory courses and encourage us to continue the development of the holo.lab. In fact, smartglass technology can be established for general use in STEM laboratory courses, but it addresses in particular some special phases like the performance of measurements or the interpretation of results. Concerning our experimental setup, we reached the feedback mentioned in Sect. 2.2, based on the interplay between the observation of data during the performance and the interpretation of the visualizations. That means, in our case, the use of the technology allows to bring forward the main part from data analysis and integrate it simultaneously into the performance without changing the setup itself. Though, we did not touch the preparation phase in a way that the consequences of the feedback could change the underlying questions or the plot of the experiment, as this would necessitate new experimental designs. These, however, could yield additional affective support via goal-based scenarios, which could bring in further possibilities to improve learning. But just respecting spatial and temporal contiguity principle already seems to have a significant influence on the way how the experiment is performed, which is mirrored in the positive results from our pilot study.

In future experimental setups for the holo.lab, more aspects of the multimedia design principles shall be integrated to reach other competencies of experimental action. For example, the preparation done by the learner could be integrated in the visualizations of the real-time data via comparing this to a hypothesized functional interrelation. Combining the signaling principle and the modality by also considering the auditory channel could end up in an AR setting not only highlighting special objects or areas of special interest, that the learner has to assemble to set up the experiment, but also providing guidance via corresponding audio commentaries. This kind of hands-on tutorial system may benefit from the affective parameters and support the construction of coherent mental models incorporating the episodic knowledge. Although in a holo.lab scenario raw data is automatically prepared and processed for the visualization, the processing itself could be extended via giving learners all possibilities of real-time graphical analysis like statistical processing (e.g., regression analysis), enabling them to extract even more characteristic values from the data to compare it to the expectations. This would shift interpretation to a whole new level, because the performance would only be marginally interrupted.

Therefore, we expect the beneficial effect of AR using smartglasses to be even bigger for more complex experiments. This assumption, however, will have to be tested in the forthcoming scenarios. Additionally, further evaluations will certainly have to capture and analyze affective and cognitive variables of the participants, especially CL, to validate our assumptions and to help to establish extensions of the multimedia principles and implications of CATLM to AR scenarios, as sketched in this contribution. Such an analysis will also have to take into account the effects of real-time interaction with different representations and real objects in the laboratory at the same time, as well as the corresponding impact on the conceptual and representational understanding of the learners. Finally, in contrast to classical multimedia learning scenarios, which mostly are intended for single users, also the aspect of cooperation between several learners becomes important in the AR framework of holo.lab experiments.

Besides this, equipping AR learning environments with self-adapting capabilities, which always ensure the best possible support for all learners, independently of their status as novice, advanced learner or expert, will also be a future goal. This, however, needs a thorough understanding of the learning process and the accompanying change of personal parameters of the learners, which is needed to construct models that are able to use collected personal data in real-time to predict the students' behavior and to deduce their competence levels.

Although AR technology with smartglasses today still is quite costly, the basic idea of a holo.lab scenario is to augment existing standard experiments widely used in STEM laboratory classes and thus to enable an easy proliferation of this technology to other laboratories at different universities or even schools, as soon as the media reach the consumer level and the mass market. The story of AR learning environments and the holo.lab has just begun.

Acknowledgment Support from the German Federal Ministry of Education and Research (BMBF) via the projects Be-greifen and gLabAssist is gratefully acknowledged.

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