Best of Germany: Smartglasses as Assistive Tools for Higher Science Education: Towards a Descriptive Model of AR-based Science Laboratories

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Abstract: Realizing augmented reality learning scenarios with smartglasses creates a wearable educational technology providing learners with active access to various kinds of additional information while keeping their hands free. Various approaches introduced those possibilities to the educational research community, but the description and categorization of those approaches remain crucial. We introduce a descriptive model based on a multidirectional communication between learner, AR system and content in the context of science laboratory experiences. Based on a framework from cognitive science, common multimedia design principles are integrated as well as domain-specific representational aspects meeting at this special educational scenario. Three different scenarios using smartglasses as AR system are being categorized to elaborate the descriptive and comparative function of the presented model. By bridging cognitive science and physics education research, we focus on key points for designing AR based learning environments.

Introduction

The worldwide research community seems to agree that immersive technologies like augmented reality (AR) or virtual reality (VR) enables educators to create new learning scenarios and to change the way how children and adults may learn (Ibáñez & Delgado-Kloos, 2018; Akçayir & Akçayir, 2017; Billinghurst & Dünser, 2012; Kuhn, et al., 2016). What makes the above-mentioned technologies special in the educational context, is the possibility of using immersive multimedia content. AR as well as VR presents learner a great variety of digitally supported contents that addresses auditory as well as visual senses in an interactive way and therefore might foster an intensive and effective learning process while respecting the individuals' learning characteristics.

At the same time, educators and researchers face many degrees of freedom when it comes to the design such learning scenarios that significantly affects every aspect of the learning processes from interactivity over transfer processes to cooperation. Without considering the possible consequences of the design, it remains impossible to formulate hypothesis or to reflect the outcomes after an application.

In recent decades, cognitive science has discovered many principles of how to design multimedia elements in educational contexts in order to address these ideas of an interactive multimodal and self-directed learning environment. Especially the Cognitive Theory of Multimedia Learning (Mayer, 2005) lead to the formulation of principles that aims at avoiding cognitive overload situations, which have been elaborated in many empirical investigations.

Furthermore, the content and the learning target is are determined by the specific context: We focus on hands-on experiences during science laboratory courses in higher education, like introductory physics lab courses (Strzys, et al., 2018).

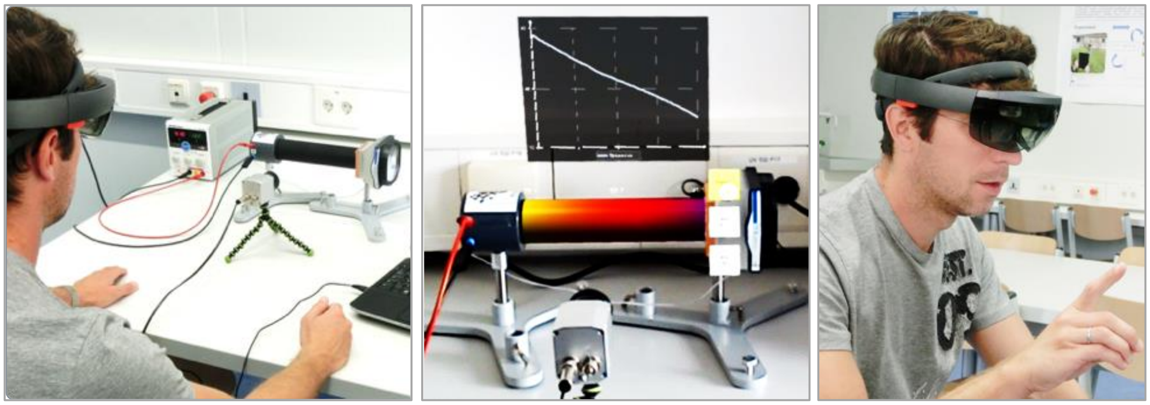

Figure 1. Pictures of an AR-based experiment examining heat conduction in metals, from left to right: Adapted setup, view through smartglasses, user with smartglasses and interactive gesture.

These special scenarios demand intense cognitive processes from learner because theories about nature meet experimental reality leading to the need of integrating different internal and external representations of the same content in order to build-up conceptual knowledge structures. This content-specific knowledge is the basis for many study-cases and has to be designed so that experts and novices both can benefit from the learning sequences.

In order to create an appropriate learning scenario, we finally have to consider ideas as well as constraints from physics education research, cognitive science and educational technology. Basic constraints are that learner have to interact with the real experimental setups and to engage in hands-on experiences while they are provided with an appropriate representational form of the content. There, the educational technology is used as an assistive system that provides real-time visualizations to support the integration of the experienced content into knowledge structures.

Meeting this triple point led to the development of smartglasses-based AR environments that displays representational forms as virtual elements in the real experimental environment (figure 1). Smartglasses, as we use them, are see-through head-mounted displays integrated in standalone devices that provide various connectivity like Bluetooth and Wi-Fi (figure 1, right). Hence, we combine the authenticity and characteristics of a traditional lab courses with the technological possibilities of providing virtual elements without distracting learners' attention from the key points of knowledge construction.

However, there is a need to describe such AR-based approaches to categorize the different way that determines the learning paths and to compare between different approaches. Most research article use the so-called "virtuality-continuum" by Milgram & Kichino (1994) to locate AR as a scenario along a one-dimensional axis between reality and virtuality (figure 2). But this reduces the complexity of those learning scenarios to one aspect that hardly describes the broad spectrum of educational aspects concerning AR learning environments.

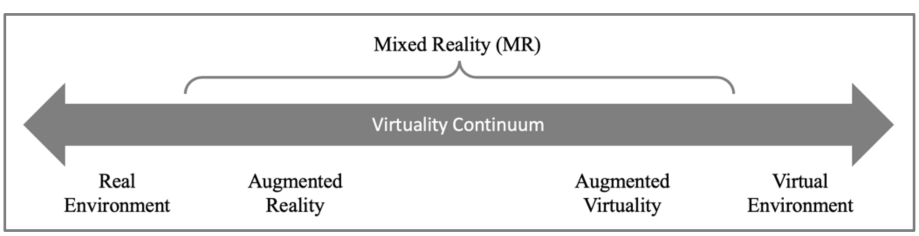

Figure 2. Simplified version of the virtuality continuum (Milgram & Kishino, 1994).

The presented work aims towards closing this gap by deriving a descriptive model that connects the three disciplines based on the exchange of multimedia messages between learner, the experimental setup and the assistive AR-system. After summarizing fundamental perspectives from multimedia learning theories and research about context-specific representations, the model is presented and applied to three different AR scenarios that uses the same technology, i.e. smartglasses, but in different experimental contexts from physics laboratory experiences, to elaborate chances and limitations of the model's descriptive function.

Theoretical Background

Multimedia Learning with Multiple Representations

In physics, more than only one representational format is often used to convey information, to support knowledge construction, and to solve problems. For an adequate comprehension of physical phenomena, concepts, and experiments, it is necessary to understand several different representations (e.g., pictures, equations, written words, diagrams, etc.) and their interconnections. Ainsworth (1999, 2006) provides a broad overview of the unique benefits given by multiple representations when people are learning complex or new ideas. According to her DeFT (Design, Functions, Tasks) taxonomy, learning with multiple representations means that two or more external representations are used simultaneously. This can include the classical text-picture-combinations that are described in the CTML, but also goes a step further by considering any other kind of combinations of external representations as well, e.g. diagrams, strobe pictures, data tables, etc. Helping students acquire representational competences is an important educational goal in many STEM domains. In particular, students need to acquire connection-making competences: they need to conceptually understand how different representations map to one another, and they need to be perceptually fluent in translating between representations (Rau, 2017). Even though multiple representations have the potential to promote learning processes, it creates also complex demands and increased cognitive load for the learners. There are many studies pointing towards students' difficulties with multiple representations (e.g., Ainsworth, 2006; Nieminen, Savinainen, & Viiri, 2010). So, for successful learning with multiple representations the cognitive load of the learning environment has to be considered and managed carefully.

This is described in the Cognitive Load Theory (CLT) (Sweller, Van Merriënboer, & Paas, 1998), which assumes the limited capacity of the working memory in terms of the amount of information that can be processed simultaneously, but also in terms of the time at which information is available for processing. According to research, e.g. by Leppink & Van der Heuvel (Leppink & Van der Heuvel, 2015), cognitive load is composed of three types:

a) Intrinsic cognitive load (ICL) refers to the complexity of the information that has to be processed and is therefore determined by the actual task as well as context-specific prior knowledge; b) Extraneous cognitive Load (ECL) is assigned to task-irrelevant cognitive processes that occupy working memory resources and can be influenced by the instructional design, e.g. how the information is presented; c) Germane cognitive load (GCL) refers to the amount of cognitive resources needed to process information into knowledge structures, i.e. the actual learning process. In recent years, researchers suggest a realignment of GCL to emphasize its "redistributive function from extraneous to intrinsic aspects of the task rather than imposing a load in its own right." (Sweller, Van Merriënboer, & Paas, 2019). We follow this argumentation and therefore we underlie a two-factor ICL/ECL model for the cognitive load during the learning process, in which GCL is an indicator for the effectiveness of the individual learning process.

Principles can be derived from the CLT which enables instructors to design (short) instructional units which are conducive to learning (Sweller, Van Merriënboer, & Paas, 2019), e.g. by keeping learning-irrelevant ECL as low as possible during the learning process. The split-attention effect (Mayer & Pilegard, 2014; Schroeder & Cenkci, 2018) implies that the spatial separation of related information sources require mental integration processes, thus increasing ECL and therefore inhibit the learning process by occupying mental resources which are no longer available for knowledge construction.

In addition to the assumption of a limited working memory capacity, the Cognitive Theory of Multimedia Learning (CTML) (Mayer, 2005) postulates two separate channels of limited-capacity working memory in which verbalized and visual- pictorial information is processed. Learning environments should be designed so that both learning channels (visual and auditory) are being addressed during the learning process. According to Mayer (2009), such multimedia instruction aims to "reduce extraneous processing, manage essential processing, and fostering generative processing". CTML further assumes that an active engagement with the subject of learning is required to form a coherent, mental representation.

To guide designers of learning instructions, Mayer (2009) identifies overall 12 instructional principles, e.g. the principle of contiguity (Mayer & Moreno, 2003) that aims to reduce extraneous processing by avoiding the split-attention effect. Hence, corresponding information should be presented in local proximity in order to avoid visual processes that would otherwise contribute to ECL (spatial contiguity principle). Equally, a temporal separation should also be set to minimum, to reduce the need of maintaining a mental representation over a longer period, i.e. representational holding (Mayer & Moreno, 2003; Clark & Mayer, 2011).

Towards a Descriptive Model

Most important requirements can be derived from analyzing the specific context that is focused during our approaches under the perspectives of the afore-mentioned theories. After summing up basic characteristics of the learning scenario, i.e. science laboratory experiences, we compose our model by describing the multidirectional communication between learner, assistive system and experiment. This step is based on a diagram by Moreno (2006) showing the processing of instructional information by humans' cognitive architecture in accordance to the CTLM.

We refer to the model as "information exchange model" (IEM). The overall aim of this model is to describe pathways of how learners receive information from the environment in order to design the scenario according to cognitive needs and constraints.

Basic Requirements

When experiencing science phenomena, the interplay between theory and experiment is a critical point in knowledge construction (Dounas-Frazer & Lewandowski, 2018). There, learners have to match already built-up ideas and pre-concepts with hands-on experienced phenomena. But this may lead to a rejection of the observations when its interpretation demands the learner to revise their pre-concepts. Hence, the role of an experiment is to consolidate leaners' concepts or to build up some kind of cognitive conflicts by demonstrating differences between theory and experimental outcomes. Therefore, it is necessary to provide learners with hands-on experiences, where they can manipulate the setups by themselves in order to address their individual needs. Finally, the learning environment has to provide an interactive experimental setup that allows to draw sound conclusions towards the domain-specific subjects.

Concerning the internal structure of the information learners are presented during the conducting, laboratory experiences seems to have an inherent split-attention format: scientific phenomena usually split up in time and space, measuring setups consist of many different devices with their own displays and characteristic delays of data processing and presentation. Eventually, from a cognitive load point of view, science experiments seems to be ill-structured with many extraneous materials and are likely to hamper active manipulation and knowledge construction when novices are faced with these complex environments. According to the split-attention-effect, an integrated arrangement of the relevant information (phenomena and data) in time and space (spatial and temporal contiguity) is needed to reduce extraneous cognitive load caused by the setup and to reduce representational holding. Given the possibilities of AR technology, the newly created learning environment should address this issue by presenting information in spatial and temporal accordance to enable learner to integrate them appropriately and reduce the risk of cognitive overload situations.

In addition, novices need a certain representational form of the presented data to be able to connect the information from the current experiment/phenomena, represented by the observation and the measurement data, to previous mental models to engage in the construction and/or revision of concepts/conceptual knowledge. The interpretation of the raw data can be enabled by an adequate representational form. An unassisted construction of a representational form different to the presented raw data would cost much mental effort that is needed as germane processes for the conceptual learning outcomes.

Furthermore, multiple representations that differ concerning the supported processes or the inherent information, should be combined so that learners will benefit from the advantages of each single representation. Multiple representations support the construction of deeper understanding when learners integrate information from them to achieve insight that would be difficult to achieve with only a single representation (Ainsworth, 2006).

In sum, our model has to take into account the following aspects: authenticity of the real experimental setup, derivation of concepts from theory-experiment-interplay, interactive engagement in the conduction and interpretation of the physical phenomena, reducing split-attention-formats by integrating information in time and space, present information in multiple representational forms to address heterogeneous knowledge levels.

Starting Point and Composition of the Model

To integrate the perspective of cognitive theories and multimedia learning, we use a flowchart by Moreno (2006) describing the perception and processing of instructional information from an instructional technology by a learning person. This diagram basically visualizes the addressing of sensory, working and long-term memory revealing the underlying cognitive structure of knowledge construction. The description of the cognitive architecture was adopted, while the visualization of the "instructional technology" is extended to a generalized description of an AR-based learning environment in the context of laboratory experiences.

For this purpose, we inserted communication pathways of how information is exchanged, i.e. where multimedia messages originate from, how they receive the learner and how the learner can take part in this process by manipulating elements. Based on the description of a multidirectional communication between learner and instructional technology by Moreno and Mayer (2007), we developed the IEM (figure 3), showing possible pathways of real and virtual content received by the learners' cognition as well as their action towards the experiment and the smartglasses. The following paragraphs elucidates the communication pathways in more detail.

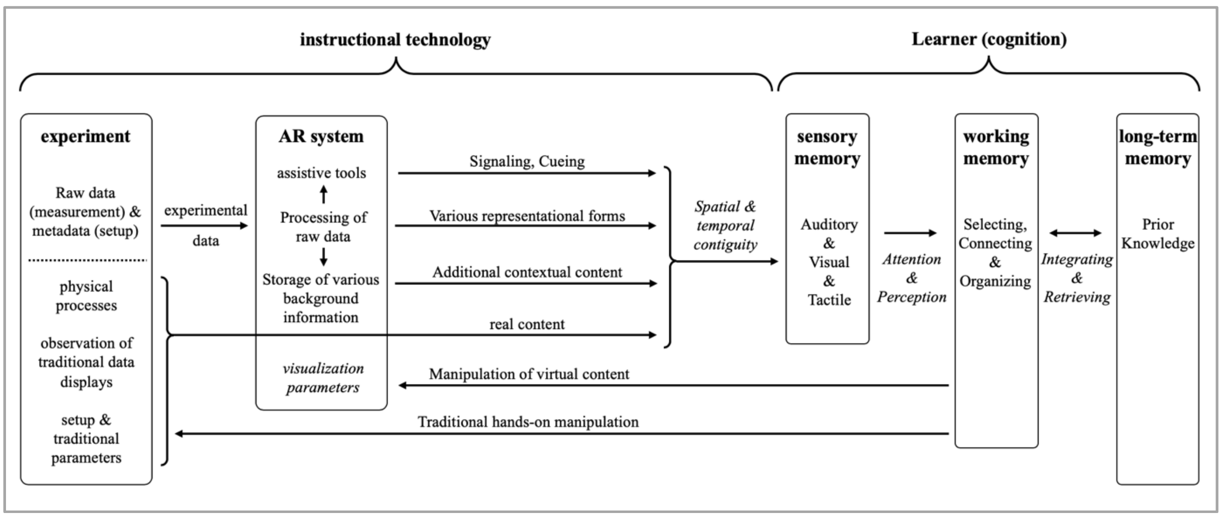

Figure 3. Information Exchange Model (IEM) for smartglasses in laboratory courses, the part of "leaner (cognition)" is adopted from R. Moreno (2006).

Experimental data: The AR system is connected to the experiment and receives raw data about the ongoing phenomena. Depending on this set of information, the AR system can provide different visualizations like various representational forms of the measurement data for interpreting the phenomena of assistive tools that are enabled if the raw data reveals that learners having trouble with the measurement processes or manipulating the setup.

Real content: Learners receive information from reality by observing the physical processes, available data displays on instruments and the setting of the utilized equipment. This "real content" is an essential part of science laboratory experiences because it provides the conduction of the physical processes. It is absolutely necessary to present the domain-specific learning content in an authentic environment.

Traditional hands-on manipulation: The manipulation of the real components of the environments represents a high percentage of the interactivity of the whole scenario. There, learners set and change basic parameters of the domain-specific experiments to manipulate the learning content.

Various representational forms: Although the learners receive information from the "real content", it might not be presented in an appropriate way to draw conclusion and to interpret the observation towards conceptual knowledge. Consequently, to enable learner to connect their pre-knowledge to the current situation, the presented information has to be visualized in alternative representational forms (Ainsworth, 2006). The AR system can pre-process raw data from the experiment and provide it as graphs, tables, animations, false colors or simple numerical values, depending on the needs of the learner and the specific context. Furthermore, physical manipulation leads to an immediate change of the measurement data according to the investigated phenomena resulting in an instant change within the visualizations or a presentation of signaling elements, providing a quasi-feedback on the leaners' own actions.

Signaling, cueing: To realize the assistive function in higher order, the AR system can present visual cues that helps learner to focus on relevant points of knowledge they might not find directly. By displaying text sequences, arrows or highlighting virtual or real elements, the system can attract learners' attention and manage their workflow. Hence, this pathway also contains a certain feedback function because

Manipulation of virtual content: If provided by the AR system, learners can manipulate virtual elements via intuitive voice- or gesture-based interaction, enabling customizable environments, e.g. by showing or hiding certain visualizations by the learners themselves. Also, learner may change the specific properties of a visualization to support observation and interpretation processes.

Spatial and temporal contiguity: All the different content elements can be combined in time and space by presenting representational forms next to the source of the data, i.e. a component or place of the phenomenon, to reduce extraneous processes that are not relevant for constructing conceptual knowledge like the search and construction of adequate visualizations. Hence, this pathway describes if the demands from multimedia learning theories were respected to support cognitive processes. The possibility of blending virtual and real components in time and space seems to be essential power of AR. Visualizations added to a traditional physics laboratory learning scenario can link physical experimentation and related scientific theory to increase students' conceptual knowledge (Dounas-Frazer & Lewandowski, 2018) and therefore link cognitive science and physics education. But there is the risk to overemphasize the communication with one part which would counteract the integration of equal information sources and therefore take away the attention from essential learning processes.

Application to Existing Learning Scenarios

In order to elaborate whether the introduced model is appropriate to describe an AR-based learning environment, three learning scenarios from physics laboratory courses were categorized. Those approaches use the same AR technology, i.e. Microsoft HoloLens as see-through smartglasses, but differ in the subject and therefore in the way, AR is used to assist the conduction of experiments and content-related learning processes. The experiments examine the topics of thermodynamics (Strzys, et al., 2017), electricity (Kapp, et al., 2019) and nuclear physics (Bodensiek, Sonntag, Wendorff, Albuquerque, & Magnor, 2019).

The first experiment deals with the heat conduction in metal rods (Strzys, et al., 2017; Strzys, et al., 2018) and is described in more detail in order to give more detail about the content of the experiment as well as the domain-specific educational aspects:

The first approach, shown in figure 1, extends a traditional experiment of investigating the heating and cooling of a metal rod via an IR-camera. Compared the traditional workflow, AR offers the possibility to see more representational forms in higher quality than the standard preview of the IR camera. Hence, learner can observe the format of temperature graph in accordance to a false color representation and three numerical values that are located above the metal rod revealing the specific increase in temperature over time (dynamic process). Because of the technology, this information is presented in real-time, while the learners' hands remain free to adjust the camera, the setup or the properties of the visualization.

The second experiment deals with basic concepts of DC circuits, i.e. Kirchhoff's Laws. In order to support the discovery of those principles, learners are also provided with real-time measurement data, which is displayed virtually above the corresponding component in various representational form like numerical values or graphs. While the hands remain free to manipulate the circuits, learners can observe the behavior of individual components as well as the whole circuit.

The third experiment examines the fine beam tube experiment to determine the charge-to-mass ratio for electrons. There, an electron beam is made visible with the help of an outer magnetic field. In addition to basic parameters of the setup, a common vector-based visualization of this magnetic field is added that extents humans' perception comparable to the temperature-revealing graph from the first experiment.

In order to compare these different approaches, a 4-point scale reaching from 0 to 3 is applied to rate the degree of fulfilling single communication pathways. 0 means that the pathway is not used at all by the environment, while 3 means, the pathway was used in the best possible way to contribute to essential learning processes.

As a consequence, we transformed the flow chart visualization of the IEM into a table format and inserted the 4-point scale as well as short description of the key points (table 1).

pathway	**AR-based approach**		
	Heat conduction	Simple electric circuits	Fine beam tube
experimental data	(2) Real-time measurement data in high resolution, but no meta data about metal rod	(2) Real-time measurement data in high resolution, but no meta data about connection of components	(1) Real-time measurement data of basic quantities, data for magnetic field not directly measured
Signaling, cueing	(0) No highlighting of key points/ components	(0) No highlighting of key points/ components	(0) No highlighting of key points/ components
Various representational forms	(2) Three domain-specific and complimentary format that are connected via the experimental setup	(1) Simple representational form to compare measurement values from all components; global aspects of electric circuits are revealed	(2) Simple representational form for measurement values, additional domain-specific visualization of electron beam and magnetic field
Additional contextual content	(0) No information about task or context	(0) No information about task or context	(0) No information about task or context
Real content	(3) Traditional setup was neither reduced by the smartglasses nor by the adapted workflow; perception was not distorted by technology	(3) Traditional setup was neither reduced by the smartglasses nor by the adapted workflow; perception was not distorted by technology	(3) Traditional setup was neither reduced by the smartglasses nor by the adapted workflow; perception was not distorted by technology
Spatial and temporal contiguity	(3) Visualizations are presented in real-time and located next to the corresponding objects	(3) Visualizations are presented in real-time and located next to the corresponding objects	(3) Visualizations are presented in real-time and located next to the corresponding objects
Manipulation of virtual content	(1) Learners are able to turn each visualization on and off separately, but no more properties	(1) Learners are able to turn each visualization on and off separately, but no more properties	(1) Learners are able to use virtual elements for measuring, but no set up of properties possible
Traditional hands-on manipulation	(1) Learners are able to change the material of the rod and to set the heating power as a basic parameter, equal to traditional workflow	(3) Learners are able to vary the structure of the circuits, change components and continuously set the source voltage	(1) Learners are able to change two basic parameters, equal to traditional workflow

Table 1. Tabular comparison of three AR-based approaches according to a 4-point scale from 0 to 3 (best).

Discussion

Table 1 reveals that the presented approaches have many things in common, like the usage of real-time measurement data to provide a visualization that displays the actual state of the physical experiment. Except the visualization of the magnetic field in the third experiment is built on an indirect but physically correct measuring process. This fundamental principle underpins the authenticity of the environment by not distracting from the key points of the action, namely the experience and observation of the phenomena – although not all of the experiments demand a high degree of interaction, caused by the traditional workflow.

In contrast, these approaches did not yet implement neither signaling or cueing techniques or additional content. These elements are very common in the context of e-learning environments such as hypermedia scripts, etc.. Even though these elements might be left out due to the inherent structure of the whole lab courses, where all the information has to be prepared by the students alone. But in order to design a highly effective learning environment, those aspect have to be considered.

All introduced approaches use the same technology, i.e. see-through visual displays, that do not affect the perception of the reality. Therefore, no communication is removed or distorted, which is not guaranteed for other technological solutions like tablet-PCs or smartphones.

Concerning the split-attention effect, all demands from cognitive theories seems to be fulfilled by realizing spatial and temporal contiguity and integrating virtual and real elements. Hence, the design of these approaches is in accordance to the design principles of the CTLM.

Eventually, the differences between the approaches are revealed under the perspective of the representational forms and the hands-on experiences. While latter is constrained by the setup itself, the design of the representation stays the core element of the domain-specific educational discussion.

Explanation of Recent Empirical Findings

Concerning the heat conduction experiment, the categorization via IEM revealed that especially the demands from cognitive science to reduce split-attention formats are respected and that the chosen representational forms are subject-specific and complementary. Hence, the content is presented in an appropriate way to engage learners in the construction of the domain-specific conceptual knowledge while the necessary cognitive processes are supported by avoiding spatial or temporal gaps. This analysis based on our descriptive model is in accordance with recent empirical investigations (Strzys, et al., 2018; Strzys, Thees, Kapp, & Kuhn, 2018), where a significant reduction of the extraneous cognitive load compared to the traditional workflow as well as a significant higher learning gain was found.

Limitations of the Model

The introduced IEM does not consider any affective variables like motivation or the emotional connection to content or assistive system. It does not reveal whether learners are afraid of the technology nor if are motivated by the interactivity of the environment. This restriction can be addressed by changing the theoretical background from CTLM to the Cognitive Affective Theory of Learning with Media, which especially includes emotional and motivational aspects. Thus, such an extension demands the development of more communication pathways because transferring or causing emotions should also be described as communication, which should be considered as a future step to complement this first approach.

Accompanying the emotional relationships, the model does not describe the communication and interaction between the learners. Technology enables them to be presented with the same visual content so that discussion about the representations as well as about the reality is equally possible. This augmentation could be included in the model by adding more participating learners, because laboratory courses are often conducted in teams.

Another communication pathway that has been reduced on purpose is the “experimental data”, which only delivers information from the experiment to the AR system but not vice versa. To respect the authenticity of the experiences, the manipulation of the experimental processes by the smartglasses is not allowed per se, which can be seen as a constraint from physics education perspective.

Furthermore, there are many more design principles derived from CTLM (Mayer & Moreno, 2003) that are not included in the current form of the model, like the segmentation principle. There, students themselves can control the transition between the individual segments of the data evaluation, i.e. the three representational forms to construct the coherent mental models, which is in accordance to the segmentation principle (Mayer & Moreno, 2003; Rey, et al., 2019).

Conclusion

Based on requirement from different research disciplines, a descriptive model for AR-based learning environment in the context of science laboratory experiences was introduced. It describes the multidirectional communication between a single leaner, the assistive AR-based system and the specific content (experimental setup) by considering the multimedia messages that a sent towards the learner and revealing interactive elements. This exchange of information was integrated in the concept of human's cognitive perception and processing as introduced by the CTLM. Each pathway can be fulfilled in different degrees that might be described by a simple rating scale. Constraints from physics education like the maintenance of traditional hands-on experiences were considered as well as the demands for avoiding split-attention format from a cognitive science point of view.

The comparison in table 1 revealed the possibilities of describing and categorizing approaches on detailed aspects that addresses key points of the design and educational consequences of those learning environments. Furthermore, the model suggests that providing an appropriate representational form addresses the domain-specific issues, while the realization of cognitive aspects can be reached by the using appropriate AR technology to present the visualization.

All in all, the model seems to meet a descriptive function in this specific context of enhanced laboratory experiences. It was possible to categorize our recent approaches and to discuss their characteristics under different perspectives that determine the quality of a multimedia learning scenario.

Nevertheless, there are still fundamental aspects of the participating discipline that are not yet integrated into the model. Especially the limitations concerning the affective variables and the cooperation between learners have to be integrated in future steps. Furthermore, causal relationships between the pathways that might be derived from underlying theories have to be empirically validated.

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