AUGMENTED REALITY FOR TEACHING AND LEARNING – A LITERATURE REVIEW ON THEORETICAL AND EMPIRICAL FOUNDATIONS

Research paper

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Abstract

Augmented Reality (AR) based teaching and learning has evolved rapidly over the past years. Researchers have shown that AR has the potential to deliver persuasive learning experiences in formal teaching (e.g., in classrooms) and in informal learning environments (e.g., museums). However, comparatively little extant research is firmly grounded in learning theories and applies rigorous empirical methods to evaluate the effect of AR on learning performance. In order to build a cumulative body of knowledge on AR-based instructional design and its effectiveness, it is necessary to consolidate both the theoretical foundations of and empirical evidence for using AR for teaching and learning. Against this background we conducted a focused systematic literature review on theoretical and empirical foundations of AR in education. We identify theory-based design elements and empirical measures for developing and applying AR teaching and learning applications and consolidate them in a design framework.

Keywords: augmented reality, learning theory, empirical studies, design framework

1 Introduction

Augmented reality (AR) refers to technologies that dynamically blend real-world environments and context-based digital information (Azuma, 1997). Recent advancements in mobile computing made AR systems affordable for the broad public. Today, mobile AR applications use head mounted displays, cameras, GPS sensors, and Internet access of smartphones and tablets to overlay real-world environments with dynamic, context-based, and interactive digital content.

With the publication of Billinghurst's AR compendium (2015), the breadth, depth and variety of extant research on AR was documented. A number of recent literature reviews have summarized the evolution of technology trends in the area of AR, have evaluated student learning with AR, have investigated the affordances of AR, and have reported about opportunities and challenges of AR in education (Bacca et al., 2014; Billinghurst et al., 2014; Diegmann et al., 2015; Chen et al., 2017) and in industry (Palmarini et al., 2018). However, although Chen et al. (2017) reported "that the number of AR studies in education has significantly increased", there is still a lack of research that is firmly grounded in learning theory and provides solid empirical evidence on how AR applications need to be designed and applied to improve learning outcomes.

On the one hand, AR is an emerging technology with high relevance for teaching, learning, and creative inquiry, thus it is expected to find broad adoption in education in the near future (Wu et al., 2013; Johnson et al., 2016). On the other hand, although in some domains (e.g., military) AR technologies have been in use for more than 50 years, it has been stated that "[d]ue to the nascent and exploratory nature of AR, it is in many ways a solution looking for a problem" (Dunleavy & Dede, 2014, p. 26) and that "relatively few research and development teams are actively exploring how mobile, context-aware AR could be used to enhance K-20 teaching and learning" (Dunleavy & Dede, 2014, p. 8).

Wu et al. (2013) aligned different instructional approaches and notions of using AR in education and emphasized the importance of learners' roles, locations, environments, and tasks. Yet, not all existing empirical studies on AR learning design are firmly grounded in learning theories. We argue that in order to build a cumulative body of knowledge on AR-based instructional design and its effectiveness, it is necessary to consolidate both the theoretical foundations of and empirical evidence for using AR for teaching and learning. Against the background of this tension between vision and reality, we conducted a systematic literature review focusing on empirical and theoretically grounded studies about the use and effects of AR for teaching and learning. Based on the findings of this review and inspired by Anderson's (2016) lens of theory applied on learning design, we propose a design framework for effective AR-supported teaching and learning.

The remainder of this paper is structured as follows: We first present the method used for our literature search and provide theoretical background on learning theories. We then outline the selection and analysis processes we applied to translate our findings into a reference framework for effective AR-based instructional design. After discussing our results, we conclude with a brief summary and directions for future research.

2 Literature search

Our systematic review was based on a database-driven literature search at the IT University of Copenhagen between May and October 2017, including the scientific databases ACM, Business Source Complete, IEEE/IEE Electronic Library (IEL), Lecture Notes in Computer Science (LNCS) and Lecture Notes in Artificial Intelligence (LNAI), SAGE Journals, Springer, and Taylor & Francis. We followed the stages provided for systematic reviews by Gough et al. (2017), consisting of the following four key activities:

1. Propose a research question
2. Ascertain and qualify relevant research
3. Critically evaluate research articles using a systematic and comprehensible process
4. Run a conclusive analysis and draw a final claim

In our focused literature review, we aimed at finding and analyzing research articles that (a) document empirical studies in which AR was used for supporting teaching and learning and (b) are grounded in learning theories. Therefore, we defined the following research question:

RQ1) Which learning theories are used as the basis for designing AR applications for teaching and learning?

2.1 Search strategy

Based on the above defined research questions, we used the search term "augmented reality" AND "theory" AND ("learn* OR teach* OR educat*") to retrieve relevant literature. This choice was driven by the focused nature of our literature review. We specifically aimed to identify studies that grounded the design and evaluation of AR applications in theories from the field of education. We are aware that through this strategy we may have missed some studies that only implicitly refer to extant theory (i.e., they do not explicitly contain the word "theory"), but as the search term produced a relatively large number of hits, this strategy seemed plausible. We limited the search to peer-reviewed scientific articles and initially found 325 database entries in various languages. Focusing on articles available in English, the database showed 291 results. After skipping duplicates and erroneous entries, like articles still not in English language or that are not peer reviewed (although this was indicated in the meta data), 184 sources remained.

2.2 Article selection

In the next step, the 184 articles were selected for cataloguing. Each article was represented by an internal serial number, the title of the article, the subjects provided by the database search tool or, when no information were given, the article's keywords. Additionally, we collected information about the source (i.e., journal or conference article), the year of publication, and added information about the main topics covered by the article. When provided in the abstract or introduction section of the article, we added information about the learning topic, the learning theory, the target group, and the number of participants in the study.

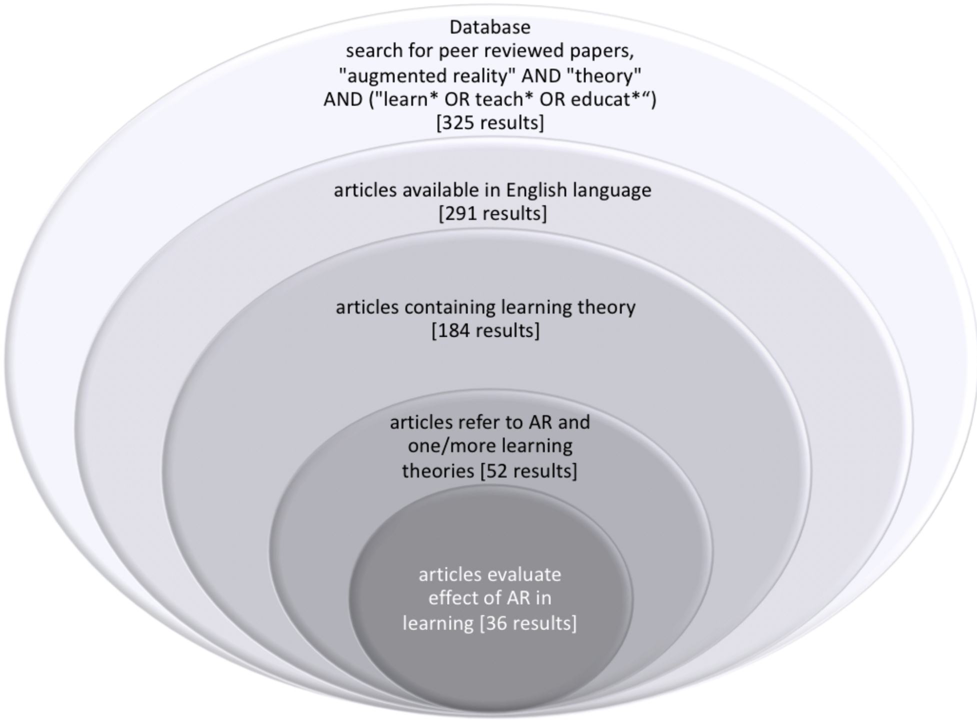

Figure 1. A visual representation of the literature search process.

We continued the selection process by browsing through the theoretical and empirical sections of the articles. Sources not providing any information about how learning theories were applied or not showing evidence for the design and use of AR technology (i.e., purely conceptual articles) were excluded. This reduced the list of articles to 52 articles. In a final screening step, we excluded articles that did not evaluate the effect of AR on learning, which left us with a final list of 36 relevant articles. Table 1 summarizes our inclusion and exclusion criteria.

Exclusion Criteria	**Inclusion Criteria**
Not a scientific source	Article was peer-reviewed
Not in English language	Article was original research in English language
Missing theoretical foundation / learning theory	Article refers to a learning theory
Not related to development of AR	Article focuses on AR development
Purely conceptual paper	Article contains a section on AR in practical use
Do not provide evaluation results	Article contains empirical results of testing AR

Table 1. Exclusion and inclusion criteria.

3 Data analysis

Our data analysis process was supported by the application of an analysis and synthesis method using a concept matrix to extract the findings (Whittemore & Knafl, 2005). We followed a concept-centric approach (Webster & Watson, 2002) and categorized the sources primarily with regards to learning theories (see Section 3.1) and learning performance measures (see Section 3.2). In addition, we extracted information about learning topics, learning environments, research methods, and standard article metadata (e.g., source, year).

3.1 Learning theories used in AR for teaching and learning

To answer research question RQ1, we categorized all sources according to learning theories. Over the past 100 years, many complementary understandings and theories about teaching and learning have emerged (Illeris, 2009, p. 7). Hence, we applied the desk reference for learning theories published by Illeris (2009) to organize learning theories. Following this approach, learning theories can be presented from a cognitive, behavioral or constructivist perspective, constituting the cognitive, social, and emotional dimensions of learning (Illeris, 2009, p. 8 ff). Accordingly, we first pruned the variety of learning theories to these three main categories and later expanded them with sub-categories representing specific learning theories identified in our review.

Behaviorism is a learning paradigm that basically follows the idea of controlling and modifying a learner's behavior and acquisition of basic facts and skills using stimulus-response pairs and selective reinforcement (Illeris, 2009). From a psychological perspective, Skinner (1974) emphasized that behavior is the basic element of learning and argued that learning theories impede the empirical research on behavior theory. Thus, radical behaviorism is rather a method of experimental analysis than a learning theory (Skinner, 1974). Even more restrictive, Jarvis (in Illeris, 2009, p. 32 ff) rejects the idea of behavior as a driving force for human learning because of the ignorance and absence of meaning in learning. In our literature analysis, we could not find a single article using behaviorist theories as the foundation for the design of AR learning evaluation.

Cognitivism is a learning paradigm that sees the mind as an information processor and focuses on internal cognitive structures to understand how information is received, organized, stored, and retrieved in the brain. Pedagogically seen, the processing and transmission of information can be executed through communication, explanation, recombination, contrast, inference, and problem solving, mainly to acquire external, existing knowledge (Anderson 1983; Wenger 1987; Hutchins 1995; Illeris, 2009, p. 203). In our data literature analysis, two cognitivist theories were identified, namely the cognitive theory of multimedia learning (CTML) by Mayer (2009) and the embodied cognitive dissonance theory [86]. In his CTML, Mayer presents three views of multimedia learning. The delivery-media view refers on the presentation of learning content using two or more devices for delivery. The presentation-modes view focus on the presentation of material using two or more presentation modes. Finally, the sensory-modality view posits that two or more sensory systems in the learner are involved. On this basis, he proposes twelve principles of multimedia design which are applicable on multimedia learning (Mayer, 2009). Not all of those principles seem to be applicable for AR learning, as shown by the studies that implemented CTML in their AR learning applications [15, 17, 19, 28, 45, 105, 172]. While seven (19%) research articles are referring to Mayer's CTML, only one study referenced the embodied cognitive dissonance theory, integrating the influence of embodied learning (e.g. effects and actions of the body and its movements) and grounded in cognition theory [86]. The authors posits, that learning takes place using a multimodal link between perception and action by coupling the environment and the brain.

Constructivism is a learning paradigm that focuses on the processes by which learners build their own mental structures when interacting with an environment (Richard, 2015; Illeris, 2009). Following a task-oriented pedagogical view, constructivism equates learning with creating meaning from experience, where learning is more meaningful to students when they are able to interact with a problem or concept. Constructivist learning theories emphasize the need to actively engage students in problem solving and motivate them through meaningful contexts. Constructivism utilizes interactive teaching strategies to create meaningful contexts that help students to construct knowledge based on their own experiences. Learning tasks are implemented by using high-order thinking skills and transferring knowledge into new situations, like used in simulated worlds, role-plays, for debating, cooperative learning, and self-directed task-based learning (Piaget, 1954; Papert, 1980; Illeris, 2009). About 28 (78%) articles were related to constructivist learning theories. In this group, we identified four subcategories, namely, situated learning, game-based learning and simulations, experiential learning, and other learning theories (e.g., variation, transformative, collaborative, and meaningful learning). Especially in terms of situated learning our categorization does not align with former assignments, i.e. Dunleavy & Dede (2014). Although they state in their review, that situated learning "… extends other learning theories …" and that "… learning is a co-constructed, participatory process …", they categorized situated learning as a learning theory on the same level next to constructivist learning theory. We understand their first argument in the way that it can also be concluded from other learning theories in our subcategories, i.e. game-based learning or simulation. Following their second argument, we understand that learning based on constructivist theory rely on constructed processes which supports the learning experience. Consequently, we allocated the four identified subcategories to constructivist learning theory.

An unexpected finding was that nine papers were referencing to more than one theory from one paradigm [6, 26, 40, 41,52,109, 110, 112, 124], and that two are referencing both cognitivist and constructivist theories [19, 28]. Consequently, creating an effective learning experience may require to incorporate ideas from more than one learning theory.

3.2 Measuring the effect of AR on learning performance

To answer research question RQ2, we worked through the articles identifying measures of learning success. The most applied measures were (the numbers in brackets refer to the sources):

- number of fulfilled tasks [1, 6, 7, 19, 20, 26, 29, 40, 51, 86, 104, 109, 157, 172, 173]
- number of right/wrong answers in a given time frame [1, 6, 7, 19, 20, 29, 40, 51, 86, 109, 172, 173]
- number of right or wrong answers [1, 6, 15, 45, 51, 52, 110, 124,125]
- answering time [45, 86, 105, 109, 172]

The answering time and number of fulfilled tasks were measured either by a human assessor or using the application itself to collect the data. To ask questions related to the learning content, most studies used tests and questionnaires to collect the number of right or wrong answers. In most cases where game-based learning and simulation were implemented, the target measures were number of fulfilled tasks given within a time frame.

Many studies also used measures of user perception to evaluate the apps:

- perceived usefulness [4, 7, 8, 15, 45, 51, 52, 104, 123, 124]
- perceived learning [7, 19, 20, 26, 40, 41, 51, 52, 110, 123]
- perceived satisfaction [15, 20, 26, 41, 51, 52, 125]
- application usability test (i.e. Shneiderman, 2010; Lewis & Sauro, 2017) [15, 27, 28, 41, 75, 123].

With regards to perceived usefulness, perceived learning, and perceived satisfaction, all studies applied a questionnaire to collect data. Some studies implemented a usability test to measure the usability of both, the application of AR and the learning content. In summary, we found no article within our literature findings that did not report any positive impact resulting from the application of AR.

Most participants in the target group were students in the age range starting from 8 years to 24 years. A wider variety within the participants were found in two studies: one field experiment in a math exhibition at a museum with 101 mixed participants between 15 and 78 years [15], and a laboratory experiment having technicians between 21 and 58 years receiving a technical training for robot programming [172]. We synthesized the learning subjects from the articles and organized them according to learning topics as shown in Table 2.

Business & Mangement	Creative Arts & Media	Health & Psychology	History	Languages & Cultures	Nature & Environment	Science, Engineering & Maths	Study Skills	Tech & Coding
economic development [173]	3D-objects [3, 123]	health-care training [8]	buildings of tobacco warehouses [51]	Chinese cultural festivals [106]	urban planning simulation [112]	science learning and motivation [17, 19, 28, 54, 77, 104]	career decisions [173]	Programming [6]
Tourism [110, 112, 123]	Architecture [44]	Tolerance [173]	History [29, 110, 123]	cultural development [110]	eco-system, ecology [4[	electrical engineering [41]	scientific thinking [77]	robot's posture [172]
	art - theory [157]	Solidarity [40]	Architecture [123]	English Filipino German Spanish vocabulary learning [1, 45, 124] Multiculturalism [52]	environmental science [77[	Mathematics [15]	natural reading and writing [75]	magnetic fields [54]
	guitar playing [86]				water circle and quality [7, 125]	astronomy, solar system [26, 105]	library knowledge [20]	Electronics [109]
					botanical garden [4[	microbial science [27]	educational choices [3]	

Table 2. Learning topics and subjects

4 Framework for an effective design of AR for teaching and learning

In the following, we will synthesize the results of the literature review in a design framework. To better link the theoretical and empirical foundations, on the one hand, with the form and function of concrete AR apps, on the other hand, we once again scanned the sources and extracted design elements that can be traced back to both abstract learning theories and concrete system features. Therefore, we examined features like learning requirements from theory, design aspects, measures, and measurement parameters. We also arranged learning theories and design elements in a logical and hierarchical structure. The extraction process started with identifying applied learning theories in each study. We categorized the research articles accordingly and analyzed the implemented design elements within each theory group, focusing on content preparation and evaluation of the learning activities and the measurement of the learning results. The details will be outlined in the following sections.

4.1 Design elements

Table 3 gives an overview of design elements organized by the theories they were derived from. The studies that have been based on CTML use different subsets of the twelve design principles outlined in this theory to translate its basic ideas into concrete features or AR apps. Sommerauer and Müller [15], for example, focused on four CTML principles by aligning physical objects and virtual content in space (spatial contiguity principle) and time (temporal contiguity principle), using trigger images in a math exhibition (signaling principle), and playing spoken words instead of displaying written words (multimedia principle) to reduce learners' extraneous cognitive load and thereby enhance their cognitive information processing processes. We found exactly the same implementation of CTML at Parhizkar et al. [28], and Santos et al. [19]. Santos et al. applied CTML as key learning theory to prepare the learning content in their Augmented Reality Learning Environment (ARLE) [19].

Design elements derived from constructivist learning theory, like proposed in Carlson & Gagnon's conceptual model [8] or in the three-phase learning model from Parhizkar et al. [28], point towards elements derived from interface design and mobile learning. Introducing mobile aspects in learning design bursts the boundaries of a single location and enables the integration of location awareness, e.g. as described in Tseng et al. (2001) and Wu et al. (2010). Such design elements would be, e.g., to include maps and features indicating objects of interest nearby, or simply to invite students to move in class, like Furió et al. [125], or to visit a specific place, as Kamarainen et al. [7] implemented in their study. We found further support for this approach in other studies [1, 20, 27, 52], but the features were described in less detail.

Furthermore, a central aim of applying AR in learning environments is to turn simple learning into a motivational learning experience [1, 3, 4, 7, 8, 17, 19, 20, 26, 27, 41, 45, 52, 77, 104, 106, 110, 123, 124, 173]. In our literature review, nearly a third of the studies implemented design elements from game-based learning and simulation, and a third from experiential learning, to achieve this goal. Prensky (2001) provided a comprehensive list of features, e.g., motivating aims that affect enjoyment, intense and passionate involvement, structure by rules, goals, interactivity and variability, feedback and gratification, competition and emotion (p. 6), supported by design elements like storytelling, accomplishing missions, or implementing variation using mini-games between learning steps. Chen & Tsai [20] used a database for game story and learning process data to analyze learner's performance and their gaming skills. Furthermore, design elements as leaderboards or badges, points and rewards are implemented to "encourage students to have fun and perform a learning" (Vizent et al., [57]).

Experiential learning is constructed in a rather process-oriented way than through single tasks. Following Kolb (2014), such a process starts with a concrete experience, which is deepened including an observation and reflection step, followed by abstract conceptualization to lead to further active experimentation. tudies from our literature search implemented, e.g., storytelling as a first instruction, followed by observations in real-world environments (e.g., botanical garden, museum, in nature), either in single or group-based tasks to later share their findings with their colleagues in class and gain further experiences in a reflection and discussion session, to finally experiment with their own and other's findings [4, 7, 27, 41, 52, 173]. situated learning incorporates learning at specific places, e.g., in a library [20], at home [45], at a botanical garden [4], in nature [7, 105, 125] or special areas in a town [29, 51, 77, 106]. The design elements therefore influence and derived from the environment itself, such as, atmosphere, impression, environmental and real world experiences, and integrate discovered objects. In addition, situated learning entail several learning activities into a learning sequence. A main difference in implementing AR learning and between our literature findings is, that learning can be an isolated individual task or a collaborative activity. Thus, the requirements for single user learning environments are different from multi-user environments. Some researchers added group-work activities (e.g. interaction between students, exploring different aspects to combine findings) in their design of the AR learning app, but often split the group tasks into individual tasks to be fulfilled by different user roles, e.g. Koutromanos & Styliaras [29] and Lundblad et al. [40], to present their findings after the AR training as a group result. Those studies incorporated no functions or tools to support active collaboration and communication inside the AR learning experience. The group activities were later realized outside the AR experience in the real environment, e.g. by having a group discussion [4, 7, 29, 52, 125]. In studies were real collaborative learning was introduced, the communication between the learners and their activities was labelled as crucial [19, 124]. Therefore, Ibáñez et al. [124] used a developer environment for multiplayer games for their AR app development. They implemented their own interface and communication module to migrate objects and users between multiple virtual environments (and the real world). However, no study incorporated any standard in their AR app design, especially for internal and/or external communication and capturing learner's behavior, activities, and results. Consequently, to design a comprehensive and persuasive framework we conclude to incorporate design elements covering the internal and external communication in AR learning applications for both, user and object communication, based on a well-established standard.

Learning theory	**Design elements for implementation**
CTML	Meyer (2009): 12 principles of multimedia design consider coherence, signalling, redundancy, spatial contiguity, temporal contiguity, segmenting, pre-training, modality, multimedia, personalization, voice, image; e.g. aligning physical objects and virtual content in space and time, using trigger images, play spoken words instead of displaying written words;

Mobile learning	Herrington et al. (2009): Design principles for mobile learning: real world relevance, mobile contexts, explore, blended, whenever, wherever, whomsoever, affordances, personalise, mediation, produse; e.g. to including maps and features indicating objects of interest nearby, inviting students to move in class or visiting a specific place;
Game-based learning & Simulation	Hirumi et al. (2010), Kiili (2005), Prensky (2001), van Eck (2006): interaction, navigation, drama and presentation, storytelling, 3-dimensional, HCI (human controller interface), programming, pattern analysis, visual content analysis; e.g. storytelling, accomplishing missions, implementing variation (e.g. using mini-games), leaderboards, badges, points, rewards;
Experiential learning	Kolb's cycle of experiential learning (2014): how information is understood and processed: diverging (feel and watch), assimilating (think and watch), converging (think and do), accommodating (feel and do); e.g. instruction, observation, reflection, experimentation using examples which connects to real-world;
Situated learning	Mc Lellan (1996): including stories, reflection, cognitive apprenticeship, collaboration, coaching, multiple practices, articulation of learning skills and technology [123]; e.g. environmental influence, atmosphere, impression, experiences

Table 3. Learning theories and design elements for implementation.

4.2 A conceptual framework

Learning is a complex process and today's concept of learning goes far beyond a simple acquisition of knowledge and skills (Illeris, 2009, p. 1). Also, emotional and social dimensions need to be included for future learning, whereas "… all learning implies the integration of two very different processes, namely an external interaction process between the learner and his or her social, cultural, or material environment, and an internal psychological process of elaboration and acquisition" (Illeris, 2009, p. 8). With our modular conceptual framework, we target to support this complexity of learning.

Based on the results of our literature review we built a design framework that is based on learning theories and additionally considers the conceptual view of Anderson of how learning and learning designs can be enhanced using emerging technologies and applying learning theories (2016, p.47). Our design framework reflects that learning consists of one or more learning sequences, which contain one or more learning activities. On the one hand, with this notion we strive to support the application of teaching-learning sequences (Méheut & Psillos, 2004), on the other hand, we enable the implementation of expanding-seeding and contracting-soloing learning sequences, as explored in organizational knowledge management systems (Bingham & Davis, 2012). Figure 2 shows a graphical representation of the proposed design framework.

The core of a learning activity in our model is to impart information and knowledge, represented as learning content. At the content layer, the learning content should be prepared applying Mayer's CTML and following any subset of the twelve principles of multimedia design (Mayer, 2009). Parhizkar et al. [28] structure their system design according to a three-phase learning model, which is partly based on CTML's design principles for content design, interface design based on constructivist learning theory, and structure design based on mastery learning strategy. We argue that the major design elements for content creation should focus on the learning content itself and be supported by cognitive theories and, therefore, be independent from aspects derived from other, e.g. constructivist, learning theories. Studies in our review that successfully constructed their learning content in this way are [15, 19, 28, 45, 105].

The integration of mobile aspects in the mobile-layer should be considered right after the step of content creation. Since most AR learning applications use mobile devices, our model includes design principles for mobile learning (Herrington et al., 2009), as demonstrated by Furió et al. [52]. At this, it is crucial to consider whether a learning application is used immovable or mobile, because this affects further design elements at the motivation level. The motivational layer considers aspects of game-based learning, simulation-based learning, and experiential learning, especially in terms of interaction and navigation and communication within and collaboration between learning activities [6, 8, 77, 123, 124]. This also lays the basis to support Kolb's elements for experiential learning [4]. Therefore, this layer includes a communication interface to collect and exchange information about users' learning experiences within the learning activity.

Finally, one or more learning activities can be assembled into a learning sequence. We included design elements following situated learning theory (which also includes collaborative learning), as proposed by McLellan (1996) and applied in the study by Chang & Jen-ch'iang [123]. Inside a learning sequence, elements of coaching, collaboration, and reflection should be included, as well as the application of multiple practices, learning skills, and technology.

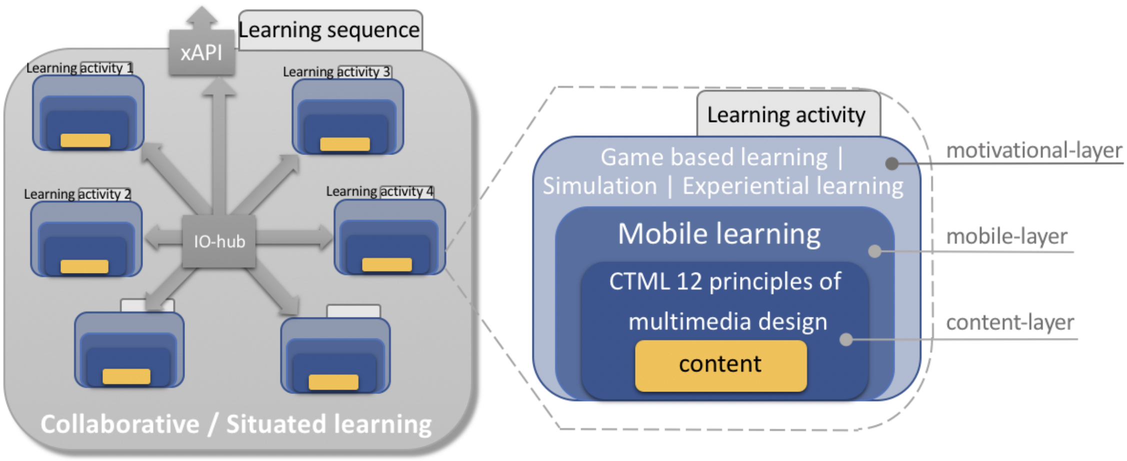

Figure 2. A graphical representation of the design framework.

4.3 Internal and external information exchange about learning experience

Connecting two or more learning activities in a learning sequence enables learning to be treated as a process. In most of the studies we analyzed, the definition and management of such processes was handled in the app itself. As already mentioned in the introduction section, future trends for AR in teaching and learning focus on measuring and evaluating learning in personalized student learning experiences, which requires to collect information about learner's behavior, activities and results and to exchange this information with external systems. Both, the internal and external process management and the communication between learning activities and with learning management systems can then be supported by the implementation of a so-called input-output hub (IO-hub). Such an approach was not implemented in any study we have analyzed, but addresses an important issue that needs to be considered to use AR in learning successfully [3, 28, 44, 75]. Lundblad et al. [40] classified data exchange as a main advantage of using mobile AR, but in their application design stored collected information locally and evaluated the results using interviews based questionnaires. When Ternier et al. [110] discussed issues encountered in terms of their mobile app's connectivity, they concluded that a network independent version would be a possible solution. However, communication between AR apps and external entities allows to collect data in form of activity statements describing the learner's behavior during the learning sequence. Thus, it addresses current challenges and future trends in AR teaching and learning.

Whenever data is collected and exchanged between entities, using established standards supports the integration of the application into various technology environments. According to the Experience Application Programming Interface (xAPI) specification, which is designed to support the information collection of formal and informal distributed learning activities (Kevan & Ryan, 2016), a data set describes single activity statements and is stored in a learning record store. In such way, series and different types of experiences can be collected to be analyzed later, including data, e.g., from wearables, mobile applications, workplace environments, and geo data (Silvers, 2017).

From a theory perspective, the xAPI specification is influenced by the socio-cultural framework Activity Theory (Silvers, 2017) and in close alignment with constructivist learning theory. For applying the xAPI standard in a learning sequence it is recommended to include it early in the design process. Thus, constructivist-aligned strategies are implemented from design through evaluation of the learning activity (Kevan & Ryan, 2016). Consequently, the data acquisition and data analysis then follow the main aspects of constructivist learning theory.

4.4 Practical application

To apply the framework in practice we mapped the design elements in retrospective to selected use cases from our literature review.

Studies that focused on content preparation implemented design elements derived from CTML [15, 17, 19, 28, 45, 105, 172]. Other studies documented their approach for content preparation less detailed but referred to CTML in a general way. For example, Santos et al. [19] stated that "multimedia learning theory provides a learning theory of how real-world annotation by AR can help students learn better based on human cognition and related processes in the brain".

Zhang et al. [26] created a 3D interactive learning environment for astronomical observation instruction using mobile AR for "3D depth and scale of astronomical and stellar configurations" for outdoor observations. Their key development principle was based on mobile learning theory, "because portable mobile devices are used, operations can be conducted and the device can be transported with no limitations on location, which reduces the influence of environmental variables on astronomical observation instruction". Moreover, they identified portability as a success factor lowering the limitations of the environment, since traditional learning software was mainly used on desktop computers or laptops, which "effectively exclud[ed] usage outdoors" [26]. In addition, they could include data derived from mobile device sensors and functions like geo positioning, compass, and angle finders "to engage in outdoor stargazing".

Studies which referred to game-based learning, like Chen & Tsai [20], Koutromanos & Styliaras [29], and Squire & Mingfong [77], implemented design elements, such as roles, stories and challenges, different places, interactive objects and tools, after they had prepared their curriculum. Similarly, Furió et al. [125] compared traditional learning with mobile game-based learning by means of mini-games. They built their lesson upon an already existing traditional classroom lesson to compare the student's performance between classroom learning and game-based learning. The learning content was prepared, e.g. by using an introduction video and several mini-games built upon mobile design elements (e.g. moving in classroom, finding QR-codes used as trigger images for specific objects), to create a game-based learning experience.

Those studies that used design elements from situated learning theory implemented these elements in addition and after the creation of single learning activities, e.g. Kamarainen et al. [7] (aid students in their understanding and interpretation of water quality measurements) and Koutromanos & Styliaras [29] (introduce buildings, their specific history and architecture). Both studies incorporated multiple learning and collaboration activities, which were designed sequentially, considering the learning content, mobile learning aspects, and game-based elements, and combined into a single situated learning experience. However, the information exchange between the single learning activities and the coordination (i.e. the sequence of the activities) were organized using traditional tasks lists, thus not implemented as a functionality within the learning application itself. Similar, elements for collaborative learning are introduced in traditional tasks, e.g., preparing group presentations in classroom.

4.5 AR learning and knowledge management

The integration of our proposed design principles into the organization and development of learning applications, e.g. for workplace trainings, contributes to the digital transformation of using and sharing organizational knowledge for both school and higher education and professional education. Thus, and addressing King's (2009) understanding of knowledge management, the design framework can be applied in education for the planning, organization, motivation and controlling of people, and to support educational processes and systems in organizations (e.g., companies and universities). Moreover, considering the framework's elements for designing a training application enables to identify and specify delivery points for submitting information during a learning activity and sequence. In this way, learning assessment becomes an integral component of the learning application design.

At this, the key to success lies in collecting the learner's data, so that it becomes possible to analyze this data to provide immediate feedback for the learner, but also for teachers and trainers at the organizational level. Integrated into learn management and knowledge management systems and combined with learning analytics tools it will potentially impact organizational learning and support knowledge management in education and training on several levels.

To apply the framework in practice, we illustrate the utilization in a use case from industry. A wide variety of companies present their organization, products, and services at international trade fairs. Operators of such fairs often need to ensure against the authorities that their staff has been instructed in safety and security issues, also considering local laws and regulations. Yet, such instructions are given either in preparation (homework) or at the office with the support of media-based trainings and followed by assessments based on multiple-choice tests. AR apps following the proposed design framework could support this task differently and more comprehensively. For example, the learning content could be provided in a cognitively efficient way (considering design elements from the content-layer), mobile features could enable learners to move around and investigate the environment from different perspectives (considering design elements from the mobile-layer), and in simulations, demonstration, and practice in the real environment (e.g., game-based elements at the motivational-layer). Furthermore, applying internal processes, tools, and equipment that is effectively utilized in practice (e.g. in learning sequences) leads finally to constructivist learning. E.g. in such simulations, safety and security procedures can be trained in that way and to ensure that people behave correctly in case of emergency. The AR learning app reports the results from learning activities to external entities in order to contribute to the need for documentation of the learning results. In such a way, the AR app also supports the organization's knowledge management system.

5 Conclusion and discussion

As shown in the previous sections, we identified the most frequently applied learning theories for designing and using AR for teaching and learning. Furthermore, we examined the remaining set of research articles concerning learning effects in relation with learning theories. However, most studies in our analysis did not apply design elements derived from learning theory in their measurement of learning. These measures can be broken down to the two, needed time and number of correct answers. In terms of analyzing the effect of AR in learning, most of the studies uses external scales and questionnaires for evaluation.

Resent publications, e.g. Bacca et al. (2014), Billinghurst & Lee (2015), Chen et al. (2017), Diegmann et al. (2015), Dunleavy & Dede (2014), Palmarini et al. (2018) and Wu et al. (2013), have illustrated that AR research spans a broad spectrum of objectives and methods. Yet, in our literature review we found only few studies that systematically rely on learning theories and empirical measures to design and apply AR for teaching and learning. Reflecting on our results shows that very few papers are reporting negative effects [172] or no positive effects [3] of using AR for learning. If negative findings are reported, they are referring to side aspects of using AR, e.g. cognitive overload [17, 109, 110], but they found a positive effect on learning [4, 20, 104,172]. However, developers of AR learning applications could learn also from negative research experiences, thus we would appreciate seeing more research results showing both, positive and negative effects.

With our proposed design framework, we aim to support the development of effective AR learning applications and which are applicable for various target groups, educational branches, and settings. Moreover, we considered the need of integrating AR learning into a manageable environment by adding design elements supporting internal and external communication and assisting instructional and organizational governance. This is strongly needed, as current and future developments on a technology level will provide new AR devices, e.g., full hands-free AR, gesture recognition, recognition of facial expressions, audio and video capturing and analysis.

Of course, our study is not free of limitations. Since we used a strict approach for identifying relevant research articles, we have probably missed articles that would have fitted to our search profile. However, we attempted to compensate for this by also relying on related recent literature reviews. A further limitation of our study and the proposed design framework could be that it only includes design elements derived from learning theories and does not incorporate additional design aspects theories not directly related to learning. Nevertheless, real world annotation, contextual visualization and vision-haptic visualization are the main strengths of AR, which are all supported by learning theories (Santos et al., 2014).

Currently, we are developing AR learning applications based on our design framework. Our future research will demonstrate the effectiveness and possible constraints of the framework and its application. Since we did not explicitly include elements for assessing the learning performance, design elements considering the measurement of learning could be a future extension, especially for measuring learning results. However, the inclusion of the xAPI in the framework already supports the collection of a learner's data, thus enables the evaluation and analysis of learning results.

Appendix: Table and overview for coding

	ID	Source	Year	pos. / neg. effect	formal / informal	Empirical method	Behaviorist	Cognitivist		Constructivist			
								CTML	grounded cognition	situated learning	game-based learning, simulation	experiential learning	other
1	1	conference	2017	pos.	formal	Classroom experiment				1			
2	3	conference	2013	none	informal	Field experiment						1	
3	4	journal	2016	pos.	informal	Field experiment						1	
4	6	journal	2015	pos.	formal	Laboratory experiment					1	1	
5	7	journal	2013	pos.	formal	Field experiment				1		1	
6	8	journal	2016	pos.	informal	Laboratory experiment				1	1		
7	15	journal	2014	pos.	informal	Field experiment		1					
8	17	journal	2017	n. a.	n. a.	Literature review		1					
9	19	journal	2014	pos.	n. a.	Literature review		1				1	
10	20	journal	2012	pos.	informal	Field experiment				1	1		
11	26	journal	2014	pos.	formal	Field experiment					1		
12	27	conference	2017	pos.	formal	Laboratory experiment						1	
13	28	conference	2012	pos.	informal	Literature review		1					1
14	29	conference	2015	pos.	informal	Field experiment				1	1		
15	40	journal	2012	pos.	informal	Field experiment					1		1
16	41	journal	2015	pos.	formal	Laboratory experiment						1	1
17	44	diss/thesis	2015	pos.	n. a.	Observation				1			
18	45	journal	2016	pos.	formal	Laboratory experiment		1					
19	51	journal	2015	pos.	informal	Field experiment				1			
20	52	journal	2013	pos.	formal	Laboratory experiment						1	1
21	54	journal	2012	pos.	formal	Observation							1
22	75	journal	2013	pos.	formal	Laboratory experiment				1			
23	77	journal	2007	pos.	informal	Field experiment					1		
24	86	journal	2014	pos.	informal	Field experiment			1				
25	104	diss/thesis	2003	pos.	n. a.	Questionnaire							1
26	105	conference	2012	pos.	informal	Observation		1					
27	106	conference	2014	pos.	informal	Field experiment				1			
28	109	journal	2010	pos.	informal	Laboratory experiment					1		
29	110	journal	2012	pos.	informal	Laboratory experiment				1			1
30	112	journal	2005	pos.	informal	Observation					1		
31	123	report	2013	pos.	informal	Field experiment				1			
32	124	journal	2012	pos.	informal	Field experiment				1		1	
33	125	journal	2015	pos.	formal	Laboratory experiment					1		
34	157	journal	2013	pos.	informal	Field experiment					1		
35	172	conference	2010	neg.	formal	Laboratory experiment		1					
36	173	journal	2010	pos.	formal	Survey						1	
∑								7	1	12	11	10	7

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