Theory-ingrained Design and Evaluation of Augmented Reality Apps for Education

Abstract. The design and evaluation of Augmented Reality (AR) learning applications is rarely grounded in learning theories and only few studies measure the effects of using AR for learning beyond subjective and self-reported measures, such as, perceived usefulness and perceived learning. From a literature review on applying AR in education, we identified design elements from learning theories and related performance measures. We follow cascading Action Design Research (ADR) cycles to development and evaluation of a first AR training prototype for AR education and training. In this paper (research-in-progress) we introduce a conceptual framework for AR application design and performance measurement and a first prototype of AR training application as an instantiation of the framework.

Keywords: Augmented Reality, Cascading ADR cycles, Design elements, Application prototype.

1 Introduction

Education is one of the most promising application areas for Augmented Reality (AR) [18]. Previous research has demonstrated that it is possible to create engaging educational experiences using AR applications (apps), both in formal and informal learning environments and for various learning topics [3, 4, 15, 18]. However, as the literature review we conducted shows, existing research on design and evaluation of educational AR apps is rarely grounded in learning theories. That is, only few researchers use learning theories as justificatory knowledge when selecting design elements regarding the form and function of AR apps, and the efficacy of these apps is often evaluated using self-reported, subjective performance measures, such as, perceived usefulness or perceived learning.

Against this background, the objectives of our research are (a) to derive a theoretically grounded framework for the design and evaluation AR learning apps from existing literature, (b) to use this conceptual framework as a blueprint to instantiate multiple prototypes of AR learning apps, and (c) to empirically evaluate the efficacy of these apps in lab and field experiments using appropriate performance measures.

Our research is embedded into two larger research projects on the application of AR in education, especially vocational education and training, that are funded by the European Union (EU). As these projects are conducted by consortia of multiple organizations concerned with the application of AR in complex educational settings, we follow the Action Design Research (ADR) method [14]. ADR is "[...] a research method for generating prescriptive design knowledge through building and evaluating ensemble IT artifacts in an organizational setting [14, p. 40]. At this, ADR tries to "make theoretical contributions and assist in solving the current and anticipated problems of practitioners" [14, p. 38].

In this research-in-progress paper, we report on the progress of our project. In particular, we present the theoretical framework that we developed based on a systematic literature review and a first prototype that embodies s subset of the design elements and performance measures that are summarized in the framework.

2 Applying ADR in project

The generic ADR process consists of four stages, namely, problem formulation; building, intervention and evaluation; reflection and learning; and formalization of learning. Each of these phases is based on specific principles and comprises well-defined tasks.

2.1 Problem Formulation

The first stage, is based on two principles: "Practice-Inspired Research" and "Theory-Ingrained Artifact" [14]. The first principle emphasizes that problems from the field can be knowledge-creation opportunities. Consequently, the researcher's intent should not only be to solve a specific instance of an encountered field problem, as a software engineer or consultant might do, but to generate general prescriptive knowledge that can be applied to solve the class of problems that the specific problem instance exemplifies. As mentioned earlier, our research is embedded into two governmentally funded projects on investigating the application of AR for supporting learning in vocational education and training. More specifically, our projects are located in the events industry, which is concerned with the organizational and technical planning and execution of large-scale events like festivals, conferences, or concerts. Location and space, including buildings, large structures (e.g., racks, trusses), and technical objects (e.g., speakers, cables), play a vital role in the events industry, which makes AR with its location-awareness and image recognition features a potentially useful technology in this context. Furthermore, the industry often works with temporary workers without formal training or qualification and international employees that travel around the globe (e.g., to follow an artist's tour). Here, the multimedia capabilities of AR offer possibilities to overcome possible language and communication problems. On the one hand, the described setting provides rich input for creating knowledge through designing solutions that are tailored to this industry. On the other hand, the fact that the projects are research projects ensures that the produced knowledge is general enough to be transferred to other contexts.

The second principle acknowledges that the design and evaluation of artifacts should be informed by existing theory, rather than solely driven by the designer's creativity. In particular, there are three ways of using prior theory in ADR: (1) to structure the problem (2) to identify solution possibilities (3) to guide the actual design [14]. In order to ensure that our design builds on prior theory, we started the project by conducting a systematic literature review on the design and empirical evaluation of AR apps in education. At this, we focused on studies that explicitly rooted their design in learning theories. In the following paragraphs, we will briefly report on the process and findings of this review.

We ran a search in the EBSCO database at the ANONYMOUS UNIVERSITY between May and November 2017 using the search term (“augmented reality” AND “theory” AND (“learn* OR teach* OR educat*”)) and limiting the search to peer-reviewed scientific articles written in English. We removed duplicates and erroneous entries from the initial results (291) and continued our selection process with the remaining 184 sources. In a first screening, we browsed through the theoretical and empirical sections of each article and excluded sources which were not related to AR, did not refer to any learning theory, were purely conceptual, or which did not conduct any empirical evaluation. This left us with a final set of 36 relevant articles.

In the subsequent data analysis, which followed Whittmore and Knafl’s method for a systematic literature synthesis [17] and Webster and Watson’s concept-centric approach [16], we aimed at identifying elements relevant for (a) designing AR learning apps and (b) measuring the effectiveness of these apps for learning. Furthermore, we focused on tracing both design elements and performance measures back to well-known learning theories, if possible.

Broadly speaking, learning theories can be classified into behavioral, cognitive, and constructivist theories [8]. In short, behaviorism focuses on controlling and manipulating learners’ behavior and sees learning as a response to external stimuli, cognitivism focuses on learners’ cognitive structures and understands learning as a process of acquiring and storing information, and constructivism focuses on supporting learners in actively creating meaning from own experiences [8].

In our review, we found three theories from the cognitive paradigm, namely the cognitive theory of multimedia learning (CTML) [12], the grounded cognition theory [10], and embodied cognitive dissonance theory [10]. Finally, we identified a variety of theories that can be classified as constructivist learning theories, for instance, experiential learning, situated learning, game-based learning and simulation. Overall, the vast majority of studies referred to constructivist learning theories (i.e., 31 out of 36), followed by cognitivist theories (i.e., 8 out of 36). While identifying kernel theories that can potentially inform the design of AR learning apps was a valuable first step in our research process, it did not provide the necessary prescriptive information needed to actually build and test such AR apps; the main reason being that the referenced learning theories were often described in too abstract and broad terms in order to translate them into tangible system features. Hence, we proceeded with extracting concrete design elements from the studies and synthesizing them in an overarching conceptual framework. We report on this step in the next section.

2.2 Building, Intervention and Evaluation

The building, intervention, and evaluation (BIE) phase was conducted in multiple cascading iterations (Figure 1).

Cycle #1. In the first cycle, we concentrated on extracting prescriptive knowledge from the studies identified in the preceding literature review. In particular, we identified design elements that describe the form and function of the AR apps and performance measures that were used to empirically evaluate the effect of using the apps for supporting learning processes. Both, design elements and performance measures, were mapped to their respective kernel theories and then summarized in a conceptual framework.

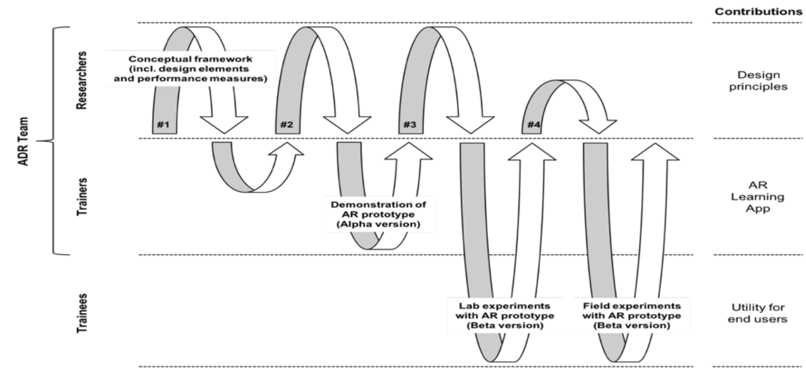

Fig. 1. Overview of Action Design Research process.

The most commonly encountered design elements were related to the cognitive theory of multimedia learning (CTML). Sommerauer and Müller [15], for instance, applied a subset of the design principles stated in CTML to inform the design of a mobile AR app for teaching mathematical concepts in the context of a museum exhibition. More concretely, they, for example, applied the spatial and temporal contiguity principles of CTML to superimpose text onto physical objects in real time when the recognizing certain trigger objects.

We also identified a variety of design elements that are rooted in constructivist learning theories. Most of these design elements can be categorized according to specific types of user interactions, for example, engaging with interactive content or communicating and collaborating with other users. Other elements were related to features known from games or simulations, for instance, design elements like missions, competitions, or leaderboards. Kamarainen et al., for example, embedded wireless-enabled mobile devices in to their AR apps to enable learning within a field trip [9]. It is important to note that some studies implemented design elements from more than one learning theory. For example, Furió et al. embedded mobile game-based learning, experiential learning theory and theory of multiple intelligences in to their AR apps for transmitting knowledge about three of the world's poorest continents to convey the idea of multiculturalism, solidarity, and tolerance [5].

To summarize the findings from the literature review we created a conceptual framework, which is depicted in Figure 2 and 3. The illustration in Figure 2 is inspired by Anderson's work on how learning can be enhanced using emerging technologies and applying learning theories [1]. At the heart of the structure are one or more learning sequences, each consisting of one or more connected learning activities. At the center of a single learning activity we have the learning content. This content should be designed according to different learning theories, indicated by the different concentric layers surrounding the learning content. At a first layer, we propose to apply the 12 design principles of CTML. In the second layer, design elements from mobile learning (e.g., Herrington et al. [6]) shall be followed. Finally, we propose to implement design elements from game-based learning [7] (e.g., leaderboard, mission), simulations (e.g., storytelling, drama), and experiential learning theory [11] (e.g., diverging, assimilating). Situated [13] and collaborative learning elements are introduced at the learning stage, where multiple learning activities are combined into a learning sequence.

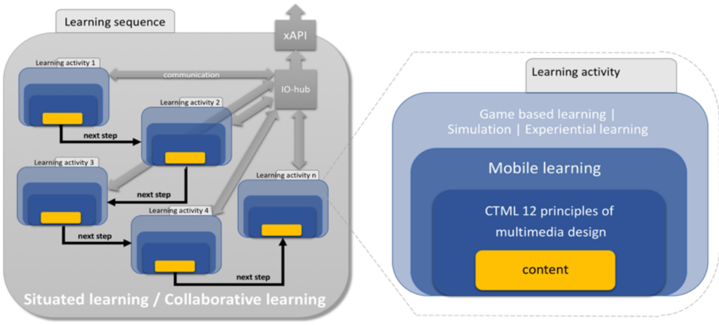

Fig. 2. Design layers in learning activities and learning sequences.

From a technical point of view, the learning sequences and activities are managed on a central platform to collect data for logging events representing the completion of learning activities and assessments. The individual AR learning apps can communicate this data via the eXperience API (xAPI [2]) and a central IO-Hub to Learning Record Stores (LRS), which can be assessed by a Learning Management System (LMS) using Learning Analytics (LA) tools.

While Figure 2 illustrates the overall architecture and structure of our proposed framework, Figure 3 give a more detailed view on the design elements and performance measures and their link to kernel theories. For example, it shows that on the interface layer we recommend to implement design elements like interactivity and communication and collaboration with other users, which can be grounded in theories on collaborative learning. In addition to design elements, the framework also contains various performance measures organized by design categories, related to the implementation stage of the learning experience. It should be noted that the design elements and performance measures listed in Figure 3 represent examples and are neither exhaustive nor completely disjoint.

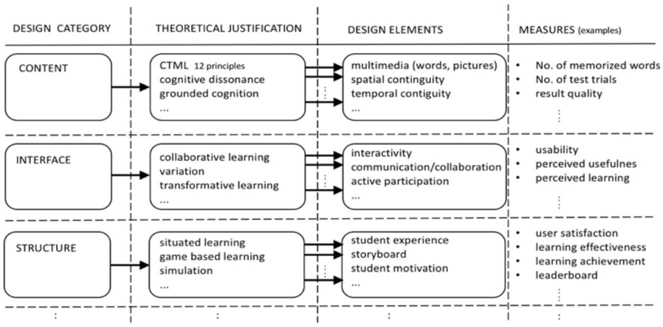

Fig. 3. Conceptual framework for theory, design elements and measures in AR learning.

Cycle #2. In the second BIE cycle, we instantiated the above described conceptual framework by developing a first AR learning app prototype. It supports the task of learning names, facts and figures, and warning notices related to physical objects used in a particular professional domain – in our case, the events industry. More specifically, the app combines machine learnings techniques for image recognition and machine translation to identify objects that are in the focus of the mobile phone camera in real-time and superimpose information such as the object's name onto the object. As training application, the app can be used in any workplace environment and the trainee can select between exploration mode or quiz mode. In both, the user needs to focus the particular object using the device's camera (e.g. smartphone, tablet, any head-mounted device). Once the object is recognized, the app provides a selection of labels, indicating the most and least likely. In quiz-mode, the trainee needs to pick the correct one. Figure 4, screenshots of the application are provided showing the explore and quiz modes.

The app design integrates design elements from CTML (i.e., the multimedia principle, the spatial contiguity principle, the temporal contiguity principle, and the signaling principle), with elements from the theory of mobile learning (i.e., users can use the app across space and time), and game-based elements (i.e., the app has a quiz mode in which users have to answers multiple choice questions by selecting the right name for a given object). From a technical perspective, the app is based on Apple's ARKit framework for implementing mobile AR experiences, Google's MobileNets model, a convolutional neural network for efficient image recognition on mobile phones, and the Google Translate API for automated translation of texts into multiple languages.

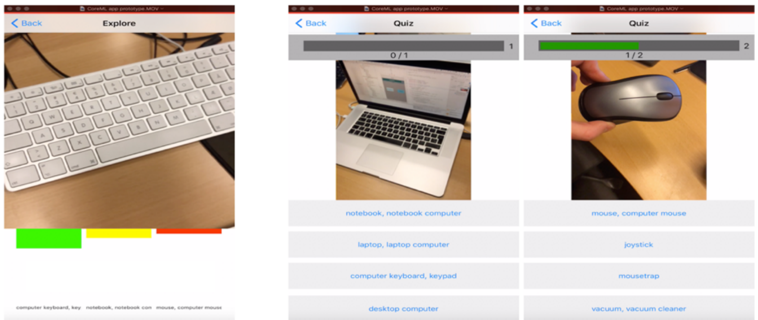

Fig. 4. AR prototype "object recognition" in action.

Currently, we are specifying experimental designs for lab and field experiments in order to evaluate the efficacy of the app. The experiments will comprise objective performance measures, such as the number of correctly identified objects or time needed to identify a certain number of objects, as well as subjective measures focusing on aspects of user experience.

3 Outlook

To design effective AR learning apps, we identified design elements and performance measures rooted in various learning theories. We synthesized these elements in a conceptual framework that can be used as a blueprint or toolbox to design and evaluate theory-ingrained AR learning apps and subsequently instantiated the framework by developing a first prototype. In future work, the prototype will be evaluated experimentally. In the final ADR phases of reflection and learning and formalization of learning, our aim is to derive theory-based and field-tested design principles that can guide other researchers in developing apps that belong to the same artifact class.

Although the framework we present is grounded in existing theory and literature, some limitations of our work have to be noted. First, we are at the very beginning in our building, intervention, and evaluation cycles and, thus, we cannot draw on empirical data to support our knowledge claims. Second, today's AR and machine learning technologies are still limited in their functionality and usability, but this situation is changing quickly. Hence, current studies provide little guidance on how AR might support learning in workplace environments in the future.

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