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Augmented reality in informal learning environments: A field experiment in a mathematics exhibition

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A R T I C L E I N F O

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A B S T R A C T

Recent advances in mobile technologies (esp., smartphones and tablets with built-in cameras, GPS and Internet access) made augmented reality (AR) applications available for the broad public. While many researchers have examined the affordances and constraints of AR for teaching and learning, quantitative evidence for its effectiveness is still scarce. To contribute to filling this research gap, we designed and conducted a pretest–posttest crossover field experiment with 101 participants at a mathematics exhibition to measure the effect of AR on acquiring and retaining mathematical knowledge in an informal learning environment. We hypothesized that visitors acquire more knowledge from augmented exhibits than from exhibits without AR. The theoretical rationale for our hypothesis is that AR allows for the efficient and effective implementation of a subset of the design principles defined in the cognitive theory of multimedia learning. The empirical results we obtained show that museum visitors performed significantly better on knowledge acquisition and retention tests related to augmented exhibits than to non-augmented exhibits and that they perceived AR as a valuable and desirable add-on for museum exhibitions.

1. Introduction

Augmented reality (AR) refers to technologies that dynamically blend real-world environments and context-based digital information. More formally, AR has been defined as a system that fulfills three characteristics (Azuma, 1997): First, it combines the real and virtual world. Second, it allows real-time interaction. Third, it aligns real objects or places and digital information in 3D. In some professional contexts (e.g., military), AR technologies have been around for more than 50 years, but only the recent proliferation and consumerization of mobile technologies (e.g., smartphones, tablets) made affordable AR systems available for the broad public. Today's mobile AR applications leverage the built-in cameras, GPS sensors, and Internet access of mobile devices to overlay real-world environments with dynamic, context-based, and interactive digital content.

It has been asserted that education is one of the most promising application areas for AR (Wu, Lee, Chang, & Liang, 2013). The NMC Horizon Report 2012 identified AR as an emerging technology with high relevance for teaching, learning, and creative inquiry and predicted broad adoption by 2015 (NMC, 2012). Yet, in a recent literature review on AR teaching and learning Dunleavy and Dede (2014) stated that "[d]ue to the nascent and exploratory nature of AR, it is in many ways a solution looking for a problem" (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" (p. 8). In fact, the majority of existing empirical research is of a qualitative nature (e.g., observations, interviews, focus groups) and concentrates on the elicitation of affordances and constraints of AR in education. Up to now, only few quantitative studies (e.g., experiments) exist that try to measure the effect of AR on learning outcomes.

In order to contribute to filing this research gap, we conducted a large-scale field experiment to test the effect of AR on learning performance. Due to its context-awareness and interactivity, many researchers see the biggest potentials in leveraging AR in informal learning environments (Dede, 2009; Greenfield, 2009), that is, voluntary and self-directed learning that takes place outside of the classroom (OECD, n.d.). We concur with this view and, therefore, conducted a field experiment at a mathematics exhibition, a typical example of an informal learning environment (Screven, 1993).

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Our experiment was driven by the hypothesis that visitors learn better from augmented museum exhibits than from exhibits that are accompanied by traditional physical information displays only (e.g., boards, posters, leaflets, quizzes, books, screens). The theoretical foundation for this hypothesis is based upon the cognitive theory of multimedia learning (CTML). We argue that AR inherently implements a subset of the design principles formulated in the CTML, namely, the multimedia principle, the spatial contiguity principle, the temporal contiguity principle, the modality principle, and the signaling principle. The empirical results we obtained provide strong evidence for our hypothesis. Museum visitors learned significantly more from augmented exhibits than from non-augmented exhibits, perceived AR as a valuable add-on of the exhibition, and wish to see more AR technologies in museums in the future.

The remainder of this paper is structured as follows. We first present theoretical background on AR in education and related experimental studies that tried to quantify the effect of AR on learning outcomes. We then describe our experimental design in detail before we come to the statistical analysis of the results. In the discussion section we compare and contrast our findings with other studies and point out directions for future research. We conclude with a brief summary and outlook.

2. Theoretical background

The cognitive theory of multimedia learning (CTML) provides potential explanations why AR may improve learning. In broad terms, CTML posits that people learn better from words and pictures than from words alone (Mayer, 1997, 2009). CTML is based on three assumptions. First, humans possess two channels for processing information, an auditory/verbal channel and a visual/pictorial channel (Paivio, 1990). Second, each channel can process only a limited amount of information at one time (Sweller, Ayres, & Kalyuga, 2011). Third, learning is an active process consisting of selecting relevant incoming information, organizing selected information into coherent mental representations, and integrating mental representations with existing knowledge (Wittrock, 1992). Based upon these theoretical assumptions, CTML postulates principles for the design of effective multimedia instructions (Mayer, 2009). We argue that AR, designed and applied in the right way, inherently incorporates a subset of these design principles, namely, the (1) multimedia principle, (2) the spatial contiguity principle, (3) the temporal contiguity principle, (4) the modality principle, and (5) the signaling principle.

The multimedia principle states that people learn better from words and pictures than words alone. AR can implement this principle by overlaying printed texts with virtual pictorial content (e.g., integrating videos into a textbook) or, vice versa, by augmenting physical objects with virtual texts (e.g., displaying labels and measures when focusing on a technical object). The spatial and temporal contiguity principles state that learning is enhanced when the space and/or time between disparate but related elements of information is minimized. AR can implement the contiguity principles by superimposing virtual content onto physical objects in real-time and thereby spatially and temporally aligning related physical and virtual information. The modality principle states that learning can be enhanced by presenting textual information in an auditory format, rather than a visual format, when accompanying related visual content. AR can implement the modality principle by playing spoken text, instead of displaying printed text, when recognizing a trigger event. Finally, the signaling principle states that people learn better when cues highlight the organization of essential information in a learning environment. AR can implement signaling by directing and guiding people through learning environments using geographic location information and visual triggers.

3. Related work

Empirical studies have examined the use AR-based technologies for teaching and learning in natural science, medicine, engineering, languages, history, arts, and other subjects and in various learning environments, for example, kindergartens, schools, universities, laboratories, museums, parks, and zoos (Dunleavy & Dede, 2014; Wu et al., 2013). Given that mobile AR is still an emergent technology and field of study, it is not surprising that the majority of these studies is of a qualitative nature (using methods such as observations or interviews) and concentrates on the elicitation of affordances and constraints of AR for teaching and learning. Up to now, only few quantitative studies exist that rigorously measure the effect of AR on learning performance. In the following, we will briefly review extant experimental studies of AR for teaching and learning. As our field experiment focused on teaching general mathematical knowledge, we focused our review on studies that looked at teaching classical K-20 learning contents and excluded studies that looked at specialized professional trainings (e.g., maintenance, repair, medical training). We also excluded studies that lacked the rigorousness of true experimental designs (e.g., control groups, sufficient sample sizes, statistical hypothesis testing). Table 1 shows an overview of the studies we were able to identify.

About half of the studies we found examined the effect of AR on learning spatial abilities; a finding that is not surprising as 3D is one of the key affordances of AR. In one of the first large-scale experiments Dünser et al. (2006) investigated the efficacy of AR for training spatial abilities using 215 high school students as participants. Applying a pretest–posttest control group design, the researchers compared an AR-based training application running on a head-mounted display with a CAD application running on a traditional computer with screen, keyboard, and mouse. A between groups comparison could not find clear evidence for the advantageousness of AR as a spatial ability learning tool. Martin-Gutierrez et al. (2010) also studied the effect of AR on learning spatial abilities using a textbook enhanced by a desktop AR system and found more promising results. In a pretest–posttest classroom experiment with 49 university students the AR group showed a significant gain in spatial abilities, whereas the control group using a traditional textbook did not show significant improvements. Finally, in a quasi-experimental study, Fonseca et al. (2014) used a mobile AR application as an educational tool in an architecture and building engineering course with 57 university students. Comparing students' final grades related to practical skills and spatial abilities with the grades of students of the same course in the previous year (control group without AR), they found a significant statistical difference indicating that the application of AR technology in the course helped to improve students' performance.

A second group of studies investigated the effect of AR on the acquisition of theoretical natural science knowledge. For example, Liu et al. (2009) conducted an experiment to measure the effect of a mobile AR application on the acquisition of ecological knowledge during a field trip to a nature park with 72 elementary school students. The researchers used a pretest–posttest design with a control group and found that the AR group significantly outperformed the control group in terms of learning improvement. Echeverría et al. (2012) compared an AR game running on tablet computers with touch screens and additional head-up displays with a multi-mice computer game running on standard PCs. In a pretest–posttest design they measured the acquisition of physics knowledge for both groups. The evaluation showed that