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# Experimenting with electromagnetism using augmented reality: Impact on flow student experience and educational effectiveness

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**Abstract:** Educational researchers have recognized Augmented Reality (AR) as a technology with great potential to impact affective and cognitive learning outcomes. However, very little work has been carried out to substantiate these claims. The purpose of this study was to assess to which extent an AR learning application affects learners' level of enjoyment and learning effectiveness. The study followed an experimental/control group design using the type of the application (AR-based, web-based) as inde-pendent variable. 64 high school students were randomly assigned to the experimental or control group to learn the basic principles of electromagnetism. The participants' knowledge acquisition was evaluated by comparing pre- and post-tests. The participants' level overall-state perception on flow was measured with the Flow State Scale and their flow states were monitored throughout the learning activity. Finally, participants' perceptions of benefits and difficulties of using the augmented reality application in this study were qualitatively identified. The results showed that the augmented reality approach was more effective in promoting students' knowledge of electromagnetic concepts and phenomena. The analysis also indicated that the augmented reality application led participants to reach higher flow experience levels than those achieved by users of the web-based application. However, not all the factors seem to have influence on learners' flow state, this study found that they were limited to: concentration, dis-torted sense of time, sense of control, clearer direct feedback, and autotelic experience. A deeper analysis of the flow process showed that neither of the groups reported being in flow in those tasks that were very easy or too difficult. However, for those tasks that were not perceived as difficult and included visualization clues, the experimental group showed higher levels of flow that the control group. The study suggests that augmented reality can be exploited as an effective learning environment for learning the basic principles of electromagnetism at high school provided that learning designers strike a careful balance between AR support and task difficulty.

**Keywords:** Secondary education; Simulations; Interactive learning environments; Applications in subject areas; Augmented reality

## 1. Introduction

Interactive technologies such as 3D virtual worlds (3DVWs) and augmented reality (AR) are potentially effective in promoting learning benefits (Conole & Dyke, 2004); they act through the mediation of usability and psychological states on learning outcomes (Choi & Baek, 2011; Dalgarno & Lee, 2010; Dickey, 2005; Dunleavy, Dede, & Mitchell, 2009; Kye & Kim, 2008; Lee, Wong, & Fung, 2010; Wu, Lee, Chang, & Liang, 2013). Therefore, an active area of research is the exploration of learning affordances offered by these emerging technol-ogies in different knowledge areas (Dalgarno & Lee, 2010; Mikropoulos & Natsis, 2011).

Augmented reality refers to technologies that enhance the sense of reality allowing the coexistence of digital information and real environments (Azuma, 1997). These technologies enable learners to interact with real objects in ways still to be discovered (Bujak et al., 2013; Cuendet, Bonnard, Do-Lenh, & Dillenbourg, 2013). However, high-quality user experiences are difficult to achieve and interaction with the learning environment should help, not hinder the teaching-learning process (Dunleavy et al., 2009; Zaharias, 2003). Many studies have reported that once high-quality interaction with the learning environment is achieved, students' emotional states contribute to improved learning effects (Billinghurst, 2003; Dalgarno & Lee, 2010; Kye & Kim, 2008; Lee et al., 2010). Furthermore, researchers have shown that AR features might increase students' motivation, engagement and their satisfaction on performing learning activities. In this regard, B. Kye and Y. Kim's conceptual model (2008) states that AR's media characteristics namely sensory immersion, navigation and manipulation might foster feelings of presence, flow state and satisfaction. Their model is similar to B. Dalgarno and M. Lee's model of learning in 3d virtual learning environments (2010) and both conclude that a positive impact of AR on emotions would improve students' cognitive processes and performance. What is lacking, however, is empirical studies to support or refute these theoretical claims (Cheng & Tsai, 2012; Dalgarno & Lee, 2010; Kye & Kim, 2008).

A full history of emotional states that emerging technologies might foster on learning activities is beyond the scope of this work. We concentrate our efforts on the observation the “optimal experience” or “flow” (Csikszentmihalyi, 1990). Flow describes a state of complete absorption or engagement in an activity that acts as a motivating factor in daily activities such as work, sport, and education (Chan & Ahern, 1999; Choi & Baek, 2011; Kye & Kim, 2008; Pearce, Ainley, & Howard, 2005). The motivation promoted by the flow state enables learners to engage in activities without receiving any apparent reinforcement (Davis, Bagozzi, & Warshaw, 1992). As this self-motivated learning is considered the best way to learn (Ghani & Deshpande, 1994), a main challenge in education is to foster learners’ flow state. In this regard, research in web-based learning environments has shown that there is a positive correlation between the flow state that students might reach when using these environments and their learning outcomes (Liao, 2006; Shin, 2006; Webster, Trevino, & Ryan, 1993). Positive results have also been highlighted by studies that analyzed the performance of students within multi-user virtual environments and game-based learning environments (Faiola, Newlon, Pfaff, & Smyslova, 2013; Papastergiou, 2009). Therefore, it is reasonable to expect that an emergent technology such as AR may also promote learners’ flow state and consequently help them to achieve better learning outcomes. Based on these concerns, this study aimed to research on the impact of AR on learners’ flow state in the context of electromagnetism, a domain area that underpins the operation of much of today’s technologies.

Electromagnetism is abstract and cognitively demanding, thus it is one of the most difficult subjects for students to master (Dori & Belcher, 2005). To understand abstract scientific concepts, students are required to build mental models where they internalize and organize knowledge structures (Dede, Salzman, Loftin, & Sprague, 1999). Unlike what happens in other Physics’ conceptual areas, when dealing with electromagnetism, students’ mental models should include abstractions and invisible factors for which students have no real-life references (Maloney, O’Kuma, Hieggelke, & Van Heuvelen, 2001). The relevance of presenting learning materials not only through words but also through visual assets to fully understand the nature of scientific phenomena and processes was reported by Dori, Hult, Breslow, and Belcher (2007). Indeed, these concerns were already addressed in the MIT Technology Enabled Active Learning (TEAL)/Studio Project where students developed much better intuition about, and conceptual models of, physical phenomena through the use of visualization in an electricity and magnetism course using web-based technologies (Belcher & Bessette, 2001; Dori et al., 2007). Consequently, developing effective pedagogical strategies and using emergent technologies for helping students in this endeavor will be a step ahead to validate TEAL Project findings when using AR technology. In this regard, augmented reality has been recognized as a technology with great potential for science learning (Bujak et al., 2013; Cheng & Tsai, 2012; Wu et al., 2013) as it provides new ways of tactile and visual interactions which could be useful to improve learning outcomes (Cheng & Tsai, 2012; Gilbert, 2005; Rapp, 2005). Visualization features of AR have been successfully used to improve spatial abilities in science and engineering (Dünser, Steinbügl, Kaufmann, & Glück, 2006; Martín-Gutiérrez et al., 2010). However, few studies have explored the visualization benefits of AR in science in general and physics in particular (Cuendet et al., 2013; Wu et al., 2013).

In response to the aforementioned issues, the aim of this study was to assess the learning effectiveness of an augmented reality experimental lesson for learning the basic principles of electromagnetism and the level of enjoyment of high school students. The lesson was designed according to the curricular objectives and subject matter of the Spanish high school Physics curriculum, and compared to a similar web-based lesson which encompasses identical learning objectives and content. Both AR and web based lessons guided the students through the building of an electromagnetic circuit representing a problem to solve which involved basic principles of electromagnetism. Each building stage offered students the possibility to review (or learn) concepts related to the proposed learning task. The AR-based lesson guided the learning workflow by leading students to build a circuit while allowing them the visualization of the forces involved and the exploration of their circuit behavior. The following research questions shaped this study:

1. Do students who use an augmented reality based lesson develop deeper understanding of the embedded basic principles of electromagnetism compared to peers who use a similar web-based lesson?
2. Do students who use an augmented reality based lesson experiment reach a flow experience higher than the one achieved by peers using a similar web-based lesson?

The study is unique in that it investigates the use of AR technology within real school settings for teaching electromagnetism at high school level, while also comparing an AR-based application with a web-based application. The study can help us to learn whether AR technology can be effective in promoting student flow, and to gain understanding on which activities maintain students’ engagement in AR-based learning environments. Furthermore, this empirical research might contribute to a better understanding of the impact of AR on learning outcomes, mainly those requiring the understanding of electromagnetic invisible forces. In addition, it can provide insight into what benefits and difficulties students found when interacting with an AR-based learning environment.

## 2. Learning affordances of augmented reality

Each interactive technology has a set of features that facilitates particular approaches to educational practice (Choi & Baek, 2011; Conole & Dyke, 2004; Dalgarno & Lee, 2010; Dickey, 2005; Dunleavy et al., 2009; Kye & Kim, 2008; Lee et al., 2010; Wu et al., 2013). For instance, three-dimensional virtual world (3DVW), an interactive technology that shares relevant characteristics with augmented reality, offers representational fidelity and learning interaction as technical features (Chittaro & Ranon, 2007). These features potentially promote learners’ psychological states such as the construction of identity, sense of presence, and co-presence, and foster the flow state (Choi & Baek, 2011; Dalgarno & Lee, 2010). As result, enhanced spatial knowledge representation, experimental learning, and collaborative learning are among the learning affordances that can be found in 3DVWs and AR learning environments (Dalgarno & Lee, 2010; Kye & Kim, 2008).

Initial attempts for analyzing the potential benefits of AR as applied to learning have been carried out. Cheng and Tsai (2012) differentiate between image-based AR and location-based AR in the context of science learning, whereas Wu et al. (2013) argue that it is better to consider AR as a concept rather than a type of technology and classified AR instructional approaches that emphasize roles, tasks and lo-cations. A psychological perspective is presented by Bujak et al. (2013) exploring physical, cognitive and contextual dimensions of these technologies. Although these studies examine AR learning affordances from different perspectives, they concur on the necessity to determine whether AR increases students' motivation, engagement and their satisfaction on performing learning activities. In this regard, B. Kye and Y. Kim's conceptual model (2008) states that AR's media characteristics namely sensory immersion, navigation and manipulation might foster feelings of presence, flow state and satisfaction once a satisfactory levels of interaction with the learning environment is achieved. Their model is similar to B. Dalgarno and M. Lee's model of learning in 3d virtual learning environments (2010). A positive impact of AR on emotions would improve students' cognitive processes and performance (Csikszentmihalyi, 1990; Efklides, Kuhl, & Sorrentino, 2001; Keller, 1979; Linnenbrink & Pintrich, 2002). Psychological states such as motivation, flow, cognitive benefits, reflection, and sense of presence are positively related to learning outcomes (Antonietti, Rasi, Imperio, & Sacco, 2000; Conole & Dyke, 2004; Dalgarno & Lee, 2010; Dunleavy et al., 2009; Lee et al., 2010). Due to the limited scope of this work, we concentrate our efforts on the observation of the psy-chological state in which an individual feels cognitively efficient, motivated, and happy, known as flow (Csikszentmihalyi, 1990), that has been widely recognized by many researchers as supportive of students' learning (Choi & Baek, 2011; Kye & Kim, 2008; Pearce et al., 2005).

Flow has been conceptualized as an optimal experience characterized by the perceived balance between challenge and skills. Nine factors have been related to this psychological state: clear goals, immediate feedback, perceived skills versus challenges, merger of action and awareness, concentration on the task, control, a loss of self-consciousness, an altered sense of time, and experience which becomes autotelic (Csikszentmihalyi, 1990). The flow concept has been applied to disciplines such as marketing, sports, work, and education (Hoffman & Novak, 2009; Novak, Hoffman, & Yung, 2000) and research conducted in web environments suggests that interactive media might foster users' flow states (Chen, Wigand, & Nilan, 1999; Cowley, Charles, Black, & Hickey, 2008). These results have encouraged researchers to study the effect of augmented reality on students' flow states (Choi & Baek, 2011; Kye & Kim, 2008; Pearce et al., 2005). Consequently, several approaches have been used to model and measure this feeling of enjoyment. The original model considers the flow state on a plot of challenge versus skill, separating the states of anxiety and boredom by the flow channel. This simple model which captures the essential principles of flow was used by Pearce et al. (2005) to measure flow as a process rather than just an overall state, as most flow measurement instruments (Chen, 2006; Jackson & Marsh, 1996; Martin et al., 2011). This two-channel model has been enhanced to include more dynamic relationships between challenges and skills. For instance, the four-channel model (Csikszentmihalyi, 1990) incorporates the apathy state to emphasize the possibility of not reaching the flow when the participant's skill level increases faster than the challenges, and the eight-channel model (Massimini & Carli, 1988) adds the states of worry, arousal, control, and relaxation to the four-channel model.

Regarding possible learning effects promoted by augmented reality technologies in education, Kye and Kim (2008) structural equation model study revealed that interaction had a direct effect on students' satisfaction, which is considered a learning affordance. Furthermore, two other psychological factors – sense of presence and flow – proved to have an influence on the application abilities of learners but to a lesser extent in knowledge and understanding factors. A similar study that outlines technological, pedagogical, and learning issues related to the implementation of AR in education focuses on students' interactions with their peers, the physical environment, and learning objects respectively (Wu et al., 2013). They claim that (1) the role-based approaches enhance the sense of presence, immediacy, and immersion which can foster engagement; (2) location-based approaches help to contextualize learning experiences; and (3) task-based approaches promote students' self-direct learning, self-motivation, problem-solving skills, and knowledge-application skills. When Cheng and Tsai (2012) analyzed augmented reality affordances for science education, they identified two major approaches for utilizing AR technology: the first one is image-based AR, and the second one is location-based AR. They concluded that image-based AR applications are useful to foster students' spatial ability, practical skills, and conceptual understanding whereas location-based AR applications tend to support scientific inquiring learning. On the other hand, an analysis by Dunleavy et al. (2009) which focused on location-based AR found that interactive, situated, and collaborative AR affordances produce highly engaging learning experiences.

In summary, AR's unique technical feature mentioned in the literature is interaction which involves view control and object manipulation. Good interactive experiences with augmented objects and eventually with peers have proved to be useful in promoting learners' emotional states, such as flow, which in turn might have positive implications for learning. Finally, among the learning effects that researches claim can be promoted by AR are improvement of knowledge, understanding, problem solving, and spatial ability.

## 3. Design of experiment

The study compared two educational applications for learning basic principles of electromagnetism to identify the effects of AR and web technologies on learning outcomes and student's task involvement. The study followed an experimental/control group design using the type of the application (AR-based, web-based) as independent variable. Students were distributed among the experimental and control groups using a random assignment.

To explore the effect of the application on students' task involvement, two dependent construct were measured: the overall-state perceived flow and the step-by-step perceived flow. Overall-state perceived flow measured the nine factors mentioned as Section 2 as affective attributes indicating a sense of flow and it was useful to examine the elements that allowed students to carry out activities in ideal conditions, optimizing satisfaction and performance. Furthermore, a closer view of the perceived tradeoff between challenge/skill was used to understand the engagement of students along the tasks (Csikszentmihalyi, 1990; Pearce et al., 2005). A pretest/posttest design was used to explore the effect of application used on students' achievement as measured by a knowledge test on basic electromagnetic concepts. To counteract order effects taking the pretest and posttest questionnaires, (a) two knowledge tests: test1 and tests2 with similar questions were designed; (b) control and experiential groups of each section were divided in two parts, half of participants completed test1 as pretest and test2 as posttest and the other half completed test2 as pretest and test1 as posttest. Finally, to explore the perceived benefits and difficulties of using the AR application to learn the basic principles of electromagnetism, an open-ended questionnaire with two open-ended questions was administered to the experimental group at the end of the learning exercise.

Based on the overview of the research literature, the specific research questions were formulated as follows:

1. Is there any difference in students' overall state of flow depending on which of the learning applications they used?
2. Are there any differences in the students' challenge-skill perception depending on which of the learning applications they used?
3. Is there any difference in students' learning outcomes depending on which of the two learning applications they used?
4. Is there any difference in students' learning outcomes for the theoretical questions and the understanding of spatial relationships among forces and electromagnetic fields depending on which of the two learning applications they used?
5. According to the participants of the experimental group, what were the students' perceived benefits and difficulties of using an AR application to learn the basic principles of electromagnetism?

### 3.1. *Participants*

In this study participated students enrolled in the 12th grade (science specialization area) at four Spanish schools which had in total five sections. The research was conducted through extraordinary sessions carried out during school hours and students' participation in the learning activity was mandatory. The sample were 64 high school students (age 17–19, $M = 17.4$, SD = 0.66). Four students did not complete some of the tests and thus were not considered for the purposes of this study. Among the 60 respondents, 15 were female and 45 were male. In each section, participants were randomly assigned to either the experimental group which tried the AR-based application, or to the control group which used the web-based application. Table 1 shows the distribution of participants according to school and intervention group.

Students had basic computer skills (e.g. elemental computer operation, the ability to use a web browser), which form part of their Computer Science curriculum. However, they never had used a tablet before.

### 3.2. *Procedure*

The study was set in five physics sections from four high schools in Spain. The sections were taught the basic principles of electromagnetism by their respective teachers who followed the same physics curriculum. All participants completed the pretest questionnaire. Two weeks after, in each of the selected schools, students were assigned to the experimental (AR-based application) or control (web-based application) groups randomly, received the corresponding application and brief oral instructions on its use. After the tutorial session, students completed the five stages of the learning activity interacting with their respective application. At the end of each stage, students completed the Pearce et al.' survey (2005). Throughout this time, students received technical and procedural help by the researchers and their physical teachers respectively. Upon completion of students intervention, students completed the posttest questionnaire, followed by the Flow State Scale. Finally, students who interacted with the AR-based application completed an open-ended questionnaire to provide feedback about perceived benefits and difficulties of using the AR-based application for learning principles of electromagnetism.

The learning activity lasted 40 min. The maximum amount of time given for the completion of the pretest and posttest questionnaires was 20 min for each one of them. The time given to complete the Flow State Scale and open-ended questionnaires was 10 min for each one of them. All the questionnaires were completed by students anonymously, in their respective classrooms, in presence of their teachers and the researchers. Neither teachers nor researchers were actively involved in the students' work. For matching of the questionnaires, pseudonyms that researchers had asked the students to adopt and write down in their questionnaires were used (see Fig. 1).

### 3.3. *Materials*

Authors designed a learning activity that allowed students to explore the effect of a magnetic field on a current-carrying wire. To this end, students were asked to solve a problem that involved the knowledge of basic concepts of electricity, magnetism, and Lorentz's law. The designed learning activity allowed students to review relevant electricity topics to the subject taught but its main focus was on helping students to understand and apply basic magnetism concepts and Lorentz's law.

Students were guided through the resolution of the problem which involved five sequential stages. Each stage was associated with one element of the electromagnetic circuit together with the problem which students had to solve: Cable, Battery, Magnet_1, Magnet_2, and Magnet_3. The narrative of the activity consisted of the construction of the circuit that solved the proposed problem by adding a new element in each stage. In order to be allowed to add a new circuit element, students were inquired about the main concepts related to that

**Table 1**
Amount of students evaluated and surveyed for school sites.

| School name | Section | Number of students | | |
|---|---|---|---|---|
| | | Experimental group | Control group | Total |
| Centro Escolar Amanecer | S1 | 6 | 6 | 12 |
| | S2 | 9 | 8 | 17 |
| IES Enrique Tierno Galván | S1 | 5 | 4 | 9 |
| IES Montes Obarenes | S1 | 6 | 7 | 13 |
| IES Pedro Duque | S1 | 6 | 7 | 13 |
| Total | 5 | 32 | 28 | 64 |

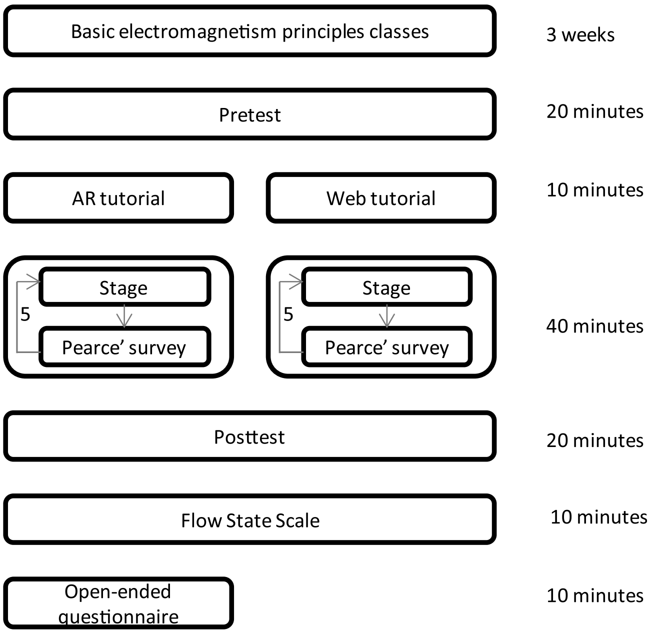

**Fig. 1.** Procedure of the experiment.

circuit element; then they had the option to read about the concepts involved with the new element included or to continue with the learning activity. Finally, students had to solve sub-parts of the proposed problem.

Two different applications were developed to support the learning activity: one application was web-based; the other application used image-based augmented reality technology. Both applications offered the same educational content and followed the same workflow according to participants' preferences and their answers to assessment items (see Table 2). Educational content included learning material (e.g. text, images) related to stages and problems to solve which were presented in the form of multiple choice or fill-in-the-blank short answer questions. However, the AR-based application allowed students to visualize electromagnetic forces upon the real environment, the web-base application did not provide this possibility.

### 3.3.1. *AR-based learning application*

The AR-based learning application was structured around students' manipulation of 3D shapes that mimicked circuit elements. Each element was tagged with a fiducial marker that enabled its recognition (see Fig. 2). The manipulation of each element had an associated specific learning material, problem(s) to solve, and for some of them simulation activities which helped students either to visualize the electromagnetic forces or to explore the circuit behavior. AR-based learning application users constructed step by step a physical paper circuit. They were allowed to visualize the electric fields, the magnetic fields and the movement of the current-carrying wire at stages battery, magnet_2 and magnet_3 respectively through the display of their tablets. Fig. 3 shows the five stages of the learning application as followed by users of the AR application and Fig. 4 shows students interacting with the AR-learning application.

The AR-based application was developed with the Apple Integrated Development Environment Xcode (https://developer.apple.com) using the Vuforia Augmented Reality Software Development Kit (https://developer.vuforia.com). The simulations were programmed using OpenGL ES 2.0 (http://www.khronos.org/opengles/2_X/) and then integrated to Vuforia.

### 3.3.2. *Web-based learning application*

The web-based learning application was an educational web-site structured around the same five stages of the AR-based application. Specifically, each stage contained the same learning objectives and educational content as the respective stage of the AR-based learning application. The learning material was accessible through navigation hyperlinks.

**Table 2**
Content of AR-based and web-based applications associated with each stage.

| Stage | Concepts | Problems to solve |
|---|---|---|
| Cable | Charge and Coulomb's Law<br>Current intensity definition, units, formula<br>Electrical resistance definition, units, formula | 1 |
| Battery | Electric field and electric potential<br>Ohm's law | 2 |
| Magnet_1 | Background on the physics of magnetism and magnets | 0 |
| Magnet_2 | Forces on moving charges in magnetic fields<br>Lorentz's Law | 2 |
| Magnet_3 | Forces on current-carrying wires in magnetic fields | 1 |

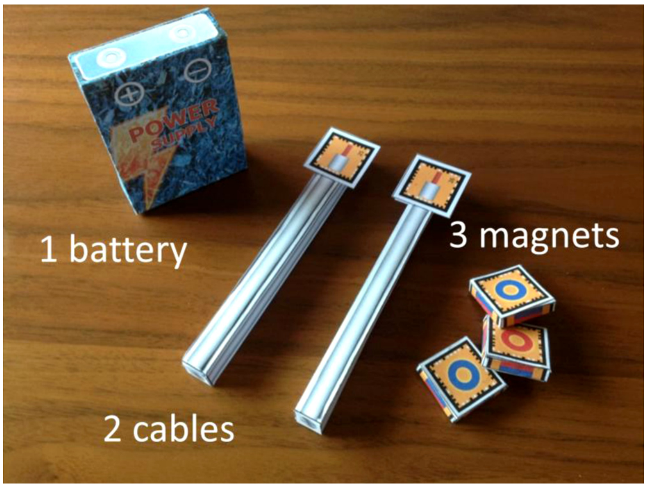

**Fig. 2.** Tangible elements of the electromagnetic circuit.

AR-based and web-based applications differed in two aspects. First, users of the web-based application arrived to stages through navigation hyperlinks, whereas users of the AR-based applications required to manipulate the physical object that mimicked an element of the circuit to begin the stage corresponding to such element. Second, the web-based application did not provide any dynamic visualization of circuit behavior.

### *3.4. Measurement instruments*

Research instruments designed and selected for this experiment aimed to understand the impact of augmented reality in learning the basic concepts of electromagnetism. In this study, flow state and learning outcomes were measured with the aim of discovering analogies and differences in flow state and learning outcomes between the experimental and the control group.

The impact of the AR application in a flow learning experience was measured in two different ways. First, as an overall state with the Flow State Scale (FSS) developed (Jackson & Marsh, 1996), adapted, and validated to Spanish language by García Calvo, Jiménez Castuera, Santos-Rosa Ruano, Reina Vaíllo, and CervellóGimeno (2008). Second, flow was measured as a process with the survey proposed by Pearce et al.(2005). The FSS contains 36 questions with 5-point Likert-scale items and provides information about nine factors which are directly related to the flow state: balance between ability level and challenge (AC); merging of action and awareness (AA); clear goals (CG); direct and clear feedback (CF); concentration on task being performed (CT); sense of control (SC); loss of self-consciousness or inhibition (LS); distortion of sense of time (DT); and autotelic experience (AE) (Csikszentmihalyi, 1990). The FSS includes as one of its factors the balance between ability level and challenge which constitutes the basic definition of flow, thus Pearce et al.'s (2005) survey was also used to monitor students' flow state throughout the learning task. Pearce et al.'s survey measured students' perception of their skills and abilities in relation to the learning tasks that they had to perform, a theoretical meaningful reference for the presence or absence of flow (Csikszentmihalyi, 1990). The survey has two question items with a five-point Likert scale that asks the level of perceived skill and perceived challenge of a task: (FQ1) How challenging did you find this last task? (FQ2) Were your skills appropriate for understanding this last task? Within the model, balance of perceived challenge and skill is considered as flow; higher perceived challenge with lower perceived skill is indicative of anxiety whereas lower perceived challenge with higher perceived skill is classified as boredom.

To assess the effectiveness of the interventions on students' electromagnetism basic concepts knowledge pretest and posttests were conducted and analyzed. The pretest and posttest comprised eight short-answer and problem solving questions. Given the difficulties to

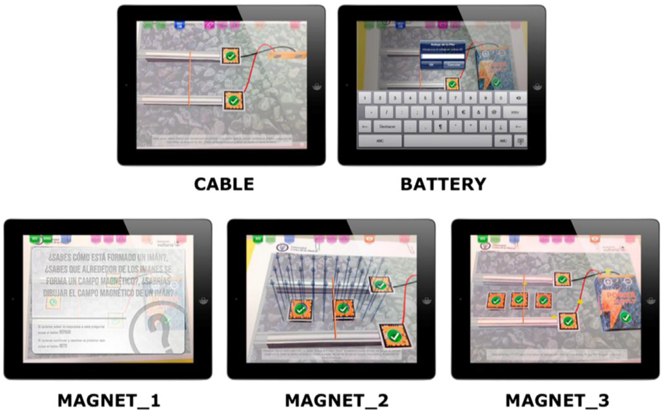

**Fig. 3.** Stages of the learning activity within the AR application.

**Fig. 4.** Students experimenting with their circuits.

understand invisible factors involved in electromagnetism (Dori & Belcher, 2005; Maloney et al., 2001), the tests included not only theoretical but also visualization questions which assessed the degree of understanding of concrete and abstract concepts involved respectively. Theoretical questions were related to the use of formulas to calculate the magnitude of physical quantities. Visualization questions assessed students' knowledge of spatial relationships among forces and electromagnetic fields. Each question was worth one point. Tests were designed by researchers and examined as to its content validity by teachers of the high schools taking part in the study. The structure of the questionnaires is presented in Table 3.

## 4. Data analysis and results

### 4.1. Research question 1

Is there any difference in students' overall state of flow depending on which of the learning applications they used?

The minimum and maximum scores of the Flow State Scale are 36 and 180 as the response scale ranges from 1 to 5. The total scores of students that used web-based and AR-based applications ranged from 104 to 161 ($M = 136.14$, $SD = 13.37$) and 96 to 156 ($M = 124.81$, $SD = 12.81$), respectively. These results indicate that overall, control and experimental group students were experimenting flow while using their respective learning applications, with results slightly more favorable for the experimental group.

The Shapiro–Wilk test of normality distribution was used to examine the distribution of the factors when the two learning applications were used. For the web-based application, all factors but LS may come from a normal distribution whereas for the AR-based application, AA, CT, SC and DT may come from a normal distribution. For those factors that followed a normal distribution in both learning applications, an unpaired-sample *t*-test was applied; for the others a Mann–Whitney Wilcoxon test was used. The Cohen's effect size index *d* (Cohen, 1988) was used to estimate the practical significant difference between groups. The Cohen's *d* values of 0.20, 0.50, 0.80, and 1.0 are considered as small, medium, large, and very large effect sizes, respectively.

Unpaired *t*-tests were applied to compare the students' flow state in the control and the experimental group over AA, CT, SC, and DT factors. Results indicate that flow differences between the two groups were statistically significant for the factors concentration on task (CT), sense of control (SC), and distorted sense of time (DT). The experimental group experienced higher levels of concentration on tasks ($M = 4.02$, $SD = 0.60$) than the control group ($M = 3.49$, $SD = 0.83$) [$t = 2.771$, $df = 58$, $p$-value $= 0.008$, $d = 0.87$]. Furthermore, AR-based application users had a higher sense of control ($M = 3.79$, $SD = 0.53$) than web-based application users ($M = 3.42$, $SD = 0.59$) [$t = -2.505$, $df = 57.923$, $p$-value $= 0.015$, $d = 0.68$]. Finally, the experimental group reported a higher distorted sense of time ($M = 3.37$, $SD = 0.92$) than

**Table 3**
Structure of the pretest and posttest questionnaires.

*Theoretical questions*
(T1) Determine the magnitude of the electric force of repulsion (or attraction) between two electrically charged particles using of the Coulomb's force law.
(T2) Definition of an electrical concept (e.g. intensity, resistance).
(T3) Determine the magnetic force of a particle in a uniform magnetic field.
(T4) Determine the resistance of a conductor and its relationship to the electric current in a circuit using Ohm's Law.
(T5) Determine the magnetic force on a current carrying wire.

*Visualization questions*
(V1) Determine the direction of charged particles in a uniform magnetic field.
(V2) Determine the direction of the electric current on a circuit.
(V3) Determine the direction of the magnetic force on a current carrying wire.

Finally, an open-ended questionnaire with two open-ended questions was issued to document students' perception of the impact that visualization and manipulation had on their learning experience: (O1) What benefits did you perceive from using the AR-based application to learn the basic principles of electromagnetism? (O2) What difficulties did you have working with the AR-based application?

the control group ($M = 2.85$, SD = 0.71) [$t = -2.392$, df = 50.366, $p$-value = 0.02, $d = 0.56$] (see Fig. 5). Therefore, the Cohen's $d$ value also suggested large, medium and medium practical effect of the difference between the two groups for the factors CT, SC and DT respectively. Since multiple tests of significance were performed, the Bonferroni correction procedure was applied to avoid making a type I error. In all factors, the level of significance was confirmed.

For the remaining factors (AC, CG, CF, LS, and AE), Mann–Whitney Wilcoxon tests were used. Results indicate that the difference between the two learning applications was statistically significant for clear and direct feedback (CF) and autotelic experience (AE). Results indicate that the experimental group had higher levels of clear and direct feedback factor ($M = 3.64$, SD = 0.48) than the control group ($M = 3.27$, SD = 0.64) [$U = 303.5$, $p$-value = 0.03, $d = 0.58$]. Similarly, the experimental group had higher values of autotelic experience ($M = 4.20$, SD = 0.71) than the control group ($M = 3.63$, SD = 0.69) [$U = 243.5$, $p$-value = 0.002, $d = 0.86$] (see Fig. 6). Therefore, the Cohen's $d$ value also suggested medium and large practical effect of the difference between the two groups for the factors CF and AE respectively.

### *4.2. Research question 2*

Are there any differences in the students' challenge-skill perception depending on which of the learning applications they used?

The analysis of the balance between ability level and challenge factor using the Flow State Scale [$W = 491.5$, $p$-value = 0.519] did not show statistical significant difference between the control ($M = 3.67$, SD = 0.52) and experimental group ($M = 3.49$, SD = 0.61). However, according to Pearce et al. (2005), representing students' flow by a single value loses valuable information about the variable experiences within a learning session. Therefore, a deeper analysis of flow experiences by learning stages could be useful to understand possible flow differences between both groups of students. In this regard, a chi-square test was performed to test the null hypothesis of no association between the flow state and the learning stage. Subsequently, a chi-square test was performed to test the null hypothesis of no association between each of the flow states and the learning application used at each learning stage; the null hypothesis was only rejected in the Magnet_2 learning stage.

An association between flow state and application stage was found when the AR learning application was used, $\chi^2 = 18.585$, df = 8, $p$-value = 0.01. The adjusted residuals associated with the flow states Boredom and Anxiety, and the application stages Cable and Magnet_3 respectively, showed that most of the students that used the AR learning application experienced boredom at the first stage of the activity (2.62) and anxiety at the last activity (3.25). The frequency measures showed that there were few students experiencing flow along the learning stages but this number increased through the evolution of the experiment (see Table 4).

For the web-based application, an association between flow state and application phase was found, $\chi^2 = 26.41$, df = 8, $p$-value $< 0.001$. The adjusted residuals associated with the flow states and the application phase data included next to the observed frequencies in Table 5 show similar results to those found with the AR-based application. Indeed, for the control group, Cable stage was also an easy challenge for students (2.53) whereas Magnet_3 was a difficult one (3.69). In the case of flow state, there were fluctuations: at some stages their values were above the expected values and in others, they were below.

The flow levels of the students were different in the experimental and control groups in stage Magnet_2. A Chi Square test showed that there was some association between students' flow states and the learning application they used during the Magnet_2 stage, $\chi^2 = 6.587$, df = 2, $p$-value = 0.03. The adjusted residuals associated with the flow states and the learning applications were included next to the observed frequencies in Table 6. The observed frequency of students who experienced boredom when using the AR-based application was 2.04 standard errors lower than would be expected if there was no association between flow state and the learning application. Similarly, the adjusted frequency of students in flow when using the AR-based application was 2.56 standard errors higher than we would expect if there was no association between flow state and the learning application. Results showed that students were less bored and more in flow state when the AR-based application was used during the Magnet_2 stage.

### *4.3. Research question 3*

Is there any difference in students' learning outcomes depending on which of the two learning applications they used?

An analysis of covariance (ANCOVA) was carried out to compare the impact of the two learning applications used. To investigate potential initial differences between groups an analysis of the pretest scores was performed. Result showed that there was no statistically significant difference between the students using the web-based application ($M = 3.375$, SD = 1.10) and the students using the AR-based application

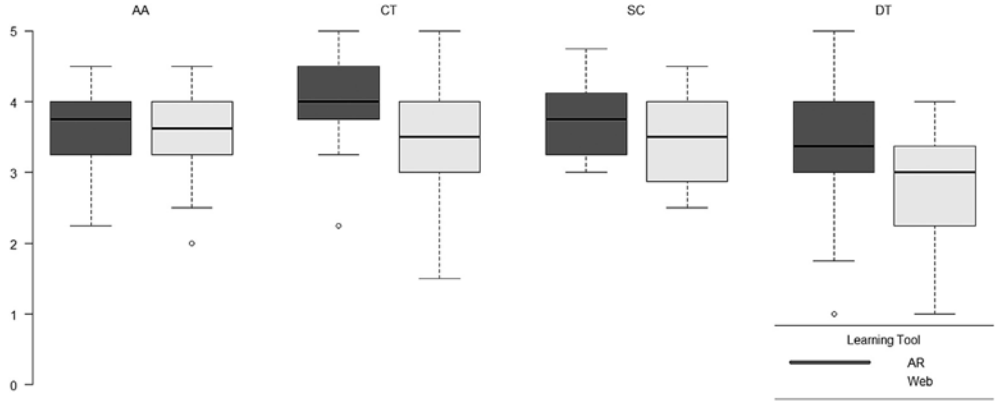

**Fig. 5.** Boxplot for flow factors: AA, CT, SC, and DT in web- and AR-based applications.

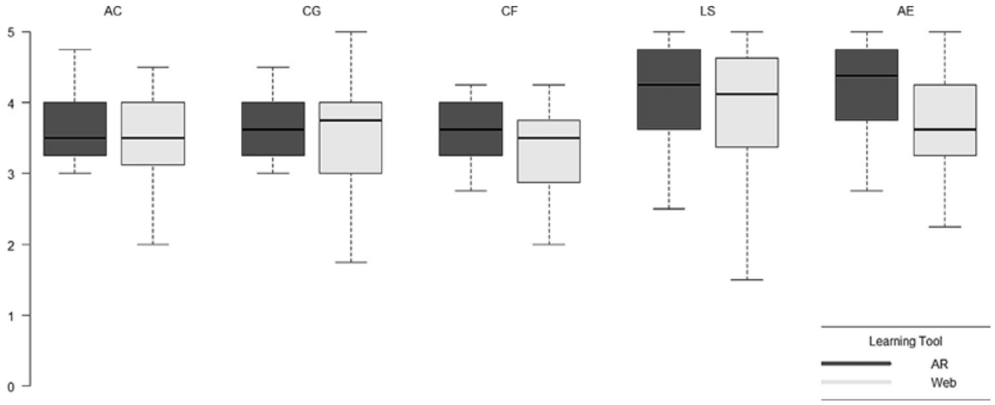

**Fig. 6.** Boxplot for flow factors: AC, CG, CF, LS, and AE in web- and AR-based applications.

($M = 3.25$, SD = 1.17), $F(1,58) = 0.181$, $p$-value = 0.672, which indicates that the two groups had similar background knowledge of the basic concepts of electricity, magnetism, and Lorentz's law.

Before conducting the analysis of covariance (ANCOVA) on posttest scores to evaluate the effectiveness of the two learning applications, preliminary verifications were performed to confirm that there was no violation of the assumptions of normality, linearity, homogeneity of variances, and homogeneity of regression slopes. The sample satisfied the requirements for analysis of covariance (web-based group = 32, AR-based group = 28). The skewness and kurtosis was between $-1.0$ and $+1.0$ for pretest and posttest scores, thus the assumption of normality is satisfied (see Table 7). Based on the test of linearity, the relationship between pretest scores and posttest scores was linear, at a statistically significant level, $F(1,58) = 57.696$, $p < .001$. The univariate general linear model procedure was used to test the significance of an interaction term in the model, made up of the covariate (pretest scores) and the factor (learning applications). The result indicated that the assumption of homogeneous regression slopes is satisfied ($F(1,56) = 0.2126$, $p$-value = 0.6465).

Results showed that there are differences in students' learning outcomes depending on which of the two learning applications they used. Indeed, students using the AR-based application performed significantly higher in the posttest than those that had used the web-based application.

### *4.4. Research question 4*

Is there any difference in students' learning outcomes for the theoretical questions and the understanding of spatial relationships among forces and electromagnetic fields depending on which of the two learning applications they used?

Pre- and posttests had two types of questions, namely theoretical and visualization questions. In order to determine whether there was any difference in students' learning outcomes caused by the type of questions depending on which of the learning application they used, the pre- and posttest scores were analyzed to distinguish between the two types of questions. The sample size satisfied the requirements for analysis of covariance (web-based group = 32, AR-based Group = 28), but the assumption of normality was not satisfied since the skewness and kurtosis was not between $-1.0$ and $+1.0$ for some of the categories (Table 8). Therefore, a Mann-Whitney-Wilcoxon non-parametric test was used to investigate potential initial differences between the control and the experimental group for the Theoretical and the visualization questions in the pretest. The statistical results indicate that the control group ($M = 2.88$, SD = 0.839) and the experimental group ($M = 2.50$, SD = 0.84) did not differ significantly on pretest theory scores ($U = 350$, $p$-value = 0.146). Similarly, there were no statistically significant difference between the control group ($M = 0.44$, SD = 0.67) and the experimental group ($M = 0.75$, SD = 0.84) on pretest visualization scores ($U = 355.5$, $p$-value = 0.125). These results indicate that the two groups had similar background knowledge of the theory and visualization of the basic concepts of electromagnetism before starting the experiment.

The paired Wilcoxon test was used to compare pretest and posttest scores within each group both for the theoretical and visualization questions. Regarding the pre- and post-test scores of theoretical questions of the control group, results indicate a statistically significant difference in their pretest scores ($M = 2.88$, SD = 0.87) and posttest scores (MD = 3.66, SD = 1.23), V = 53, $p$-value = 0.004. For the experimental group, results also indicate a statistically significant difference in their pretest scores ($M = 2.50$, SD = 0.84) and posttest scores (MD = 3.89, SD = 0.79), V = 6, $p$-value $< 0.001$. Thus, both groups improved their scores in theoretical questions. In order to analyze learning benefits in the use of formulas to calculate the magnitude of physical quantities when using the AR-based application ($M = 3.89$, SD = 0.79) compared to the web-based application ($M = 3.66$, SD = 1.23), a Mann–Whitney Wilcoxon test was used. Results indicate that the control and experimental groups did not differ significantly on posttest scores related to the theoretical questions ($U = 422.5$, $p$-value = 0.6961).

Regarding the pre- and posttest scores of visualization questions, results indicate a statistically significant difference in pretest scores ($M = 0.44$, SD = 0.67) and posttest scores (MD = 1.34, SD = 1.04) when the web-based application was used (V = 14, $p$-value $< 0.001$). For the

**Table 4**
Observed frequencies and adjusted residuals for students using the AR application.

| | Cable | Battery | Magnet_1 | Magnet_2 | Magnet_3 |
|---|---|---|---|---|---|
| Boredom | 19(2.62) | 13(0.08) | 14(0.51) | 11(-0.76) | 7(−2.46) |
| Flow | 6(−2.08) | 11(0.09) | 12(0.52) | 14(1.39) | 11(0.09) |
| Anxiety | 3(−081) | 4(−0.23) | 2(−1.39) | 3(−0.81) | 10(3.25) |

**Table 5**
Observed frequencies and adjusted residuals for web application.

| | Cable | Battery | Magnet_1 | Magnet_2 | Magnet_3 |
|---|---|---|---|---|---|
| Boredom | 23(2.53) | 14(−1.02) | 18(0.55) | 21(1.74) | 7(−3.79) |
| Flow | 8(−0.69) | 13(1.47) | 9(−0.26) | 6(−1.55) | 12(1.03) |
| Anxiety | 1(−2.46) | 5(−0.41) | 5(−0.41) | 5(−0.41) | 13(3.69) |

AR-based group, results also indicate a statistically significant difference in pretest scores ($M = 0.75$, $SD = 0.84$) and posttest scores ($MD = 2.21$, $SD = 0.96$), $V = 12$, $p$-value$< 0.001$. Thus, both groups improved their scores in the visualization questions. To analyze learning benefits for questions related to spatial relationships among forces and electromagnetic fields when the AR-based application ($M = 2.21$, $SD = 0.96$) compared to the web-based application ($M = 1.34$, $SD = 1.04$), a Mann–Whitney Wilcoxon test was used. The AR-based group ($M = 2.21$, $SD = 0.96$) reported significantly higher posttest scores for visualization than the web-based group ($M = 1.34$, $SD = 1.04$), $U = 248$, $p$-value $= 0.001$.

Thus, there were differences in students' learning outcomes depending on which of the two learning applications they used.

### 4.5. Research question 5

According to the participants of the experimental group, what were the students' perceived benefits and difficulties of using an AR application to learn the basic principles of electromagnetism?

The open-ended questionnaire included two questions to inquire about the benefits and difficulties perceived by students when using the AR application. The data gathered (42 responses from 14 students) was examined using an open coding scheme (Strauss & Corbin, 1998). Comments related to benefits revealed two major themes: academic (11) and affective (19); however, the comments related to difficulties referred to usability (8) and cognitive (4) issues.

The majority of affective benefits perceived by users of the AR application pertained to the use of the tablet and the real objects (8 responses). Affective benefits mentioned were related to a sense of well-being (14) and factors associated with motivation through the learning activity (5). Benefits reported were linked to different features of the application. The visual capabilities of the application were mentioned in six responses. Five students highlighted the affective benefits of learning and practicing with the AR-application when comparing it with the traditional way of learning.

Examples of responses relating to affective benefits:

*"I liked it; it was like a game to build the circuit in my tablet."*

*"It is stimulating to add new elements to the circuit; you have the feeling of success."*

*"It is an amazing use of tablets. We can practice these lab exercises also at home."*

*"It felt rewarding when I saw how my solution worked properly."*

*"I enjoyed building the circuit, experimenting with its parts and observing the changes produced."*

*"This is a fun way to learn, it is better than study with my book."*

Regarding the cognitive benefits perceived by users of the AR application, four students highlighted that the application helped them to better understand the circuit operation; three students remarked that the application was useful for keeping concentration; two comments were related to advantages of having real-time feedback to evaluate their progress and other students claimed that similar learning activities would help them to learn with less effort.

Examples of responses relating to academic benefits:

*"Visualizing forces helped me to understand the behavior of the circuit."*

*"I could understand better how to solve the problem thanks to the possibility to experiment with the circuit elements."*

*"Building the circuit by myself helped me to focus my attention on the problem to solve."*

*"It helped me to see whether or not I was doing well, if I applied correctly the formulas."*

*"I could learn Lorentz's Law with less effort than studying at home."*

Some students reported they had difficulties while completing the learning activity. Two main usability problems arose: (1) the most common difficulty for students was to make the system recognize the markers (seven students), and (2) three students experienced problems manipulating the tablet and the physical objects representing the components of the circuit at the same time. Both problems were easily solved with the help of instructors. Finally, two students reported that they lost concentration when they had the option to read review information.

**Table 6**
Frequency and adjusted residuals for Magnet_2 learning stage.

| | Boredom | Flow | Anxiety |
|---|---|---|---|
| AR-based application | 11(−2.04) | 14(2.56) | 3(−0.55) |
| Web-based application | 21(2.04) | 6(−2.56) | 5(0.55) |

**Table 7**
Descriptive statistics of pretest and posttest scores for control and experimental groups.

| Test | Learning application | *n* | Mean | SD | Median | Trimm | Skew | Kurtosis |
|---|---|---|---|---|---|---|---|---|
| Pretest | Web-based | 32 | 3375 | 1.10 | 3 | 3.35 | 0.24 | −0.30 |
| | AR-based | 28 | 3250 | 1.17 | 3 | 3.21 | 0.32 | −0.56 |
| Posttest | Web-based | 32 | 5000 | 1.87 | 5 | 5.12 | −0.35 | −0.62 |
| | AR-based | 28 | 6110 | 1.40 | 6 | 6.17 | −0.50 | −0.81 |

After adjusting the posttest scores in the pretest (covariate), the following results were obtained. A statistically significant main effect was found depending on the learning application used on the posttest scores, $F(1{,}57) = 6.645$, $p$-value $= 0.012$, in favor of the group using the AR-based application. Partial eta squared values were obtained from the ANCOVA test in order to determine the effect size of the learning tool used (AR- or web-based) on the posttests scores. The partial eta squared values of 0.01, 0.06, and 0.14 are considered as small, medium, and large effect sizes, respectively. Partial $\eta^2 = 0.1044$ obtained suggested a nearly large practical effect of the difference between the two groups.

Examples of responses relating to the difficulties encountered:

“I had problems to make the system recognize the battery.”

*“I was confused sometimes when the system failed to recognize elements previously recognized.”*

*“I wish I had a stand for the tablet, I was tiring to keep it in one hand while I was manipulating the elements of the circuit.”*

*“Going back and forth from reading information, to touch the tablet and manipulate objects, made me lose concentration sometimes.”*

Students were exposed to and required to quickly apply multiple skills: handheld and object manipulation, solving physics problems presented within a narrative and with no training. Most of them were able to do it easily, in a very natural way. However, a short training session would have helped to reduce the frequency of problems encountered by the others.

## 5. Discussion and conclusions

This study presented and evaluated an augmented reality learning application to learn the basic concepts of electromagnetism. The study compared the AR-based application with its equivalent web-based application in order to study its learning effectiveness and students’ level of enjoyment. Both applications were designed to provide the same information and workflow capabilities. The main findings and their implications are discussed below.

With respect to the overall flow state achieved by both groups of learners, the statistical results of this study indicate that participants who used the AR-based application were more likely to experience positive moods following the learning activity than those using the web-based application. From the analysis of the nine factors underlying users’ flow experiences, the experimental group showed higher levels of concentration on the task (CT) and distorted sense of time (DT) than the control group, which might have led to the students achieving deep learning (Liu, Cheng, & Huang, 2011). This result is consistent with the comments provided by AR-based application users who claimed that one of the main advantages of using AR was that it helped them to concentrate in the tasks while they were building the circuit step by step. Further studies are necessary to determine whether the manipulation features of AR in this learning context promote students’ concen-tration. In general terms, discovering the impact of each AR feature in flow factors will be useful to guide the design of better AR-based learning applications. Statistical results also show that the experimental group had a better sense of control (SC) and clearer direct feed-back (CF) than the control group, which can be beneficial for the recall of information, according to Bujak et al.’s (2013) study. Indeed, students said that interacting with real objects in the AR application was a natural activity which allowed them to build a circuit step by step and verify its physical properties in real time. However, a usability problem could have a negative influence on these results as some participants mentioned they had difficulties handling the tablet and the real objects simultaneously. This drawback could be solved by introducing stands for the tablets, thereby reducing extraneous cognitive load (Zaharias, 2003). Finally, participants in the AR-based learning activity reported the highest levels of intrinsic satisfaction (AE) compared to those who used the web-based application; this may have helped the experimental group to perform the task more easily that the control group. Those empirical findings corroborate theoretical claims about flow affordances of augmented reality on learning (Bujak et al., 2013; Cheng & Tsai, 2012; Dunleavy et al. 2009; Kye & Kim, 2008). However, not all the factors seem to have influence on learners’ flow state, this study found that were limited to: concentration, distorted sense of time, sense of control, clearer direct feedback, and autotelic experience. Therefore, the design of AR-learning application should consider the strengths and limitations of affective learning affordances of this emergent technology to deploy effec-tive learning environments.

**Table 8**
Descriptive statistics of pretest and posttest scores by intervention learning application and question type.

| Test | Learning application | *n* | Question type | Mean | SD | Median | Trimm | Skew | Kurtosis |
|---|---|---|---|---|---|---|---|---|---|
| Pretest | Web-based | 32 | Theoretical | 2.88 | 0.87 | 3 | 2.88 | −0.05 | 0.11 |
| | | | Visualization | 0.44 | 0.67 | 0 | 0.31 | 1.16 | 0.03 |
| | AR-based | 28 | Theoretical | 2.50 | 0.84 | 3 | 2.50 | −0.36 | −0.71 |
| | | | Visualization | 0.75 | 0.84 | 1 | 0.67 | 0.82 | −0.22 |
| Posttest | Web-based | 32 | Theoretical | 3.66 | 1.23 | 4 | 3.81 | −0.75 | −0.37 |
| | | | Visualization | 1.34 | 1.04 | 1 | 1.31 | 0.32 | −1.11 |
| | AR-based | 28 | Theoretical | 3.89 | 0.79 | 4 | 3.92 | −0.27 | −0.54 |
| | | | Visualization | 2.21 | 0.96 | 3 | 2.29 | −0.66 | −1.08 |

From the analysis of the factor that measured the balance between ability level and challenge within the Flow State Scale, no statistically significant difference between the two groups was found. However, the study specifically collected the perception of students regarding skills and challenge with a two question survey applied at the end of each learning stage (Pearce et al., 2005). Flow imbalances among the learning stages were found to be mainly associated with the perceived difficulty of the content and the form of interaction with the application. The first stage was perceived as boring and it was devoted to reviewing content through the touching interface provided by the tablet; no experimentation was included in the AR version of this first stage, thus both groups were exposed to similar conditions and similar results were found. On the other end of the spectrum was the last stage which required applying the knowledge acquired in previous stages of the learning activity and caused anxiety to participants. The final simulation activity included in the AR application where students could observe how the circuit behaved according to their solution was not perceived as sufficient to help them to overcome the final challenge. Finally, the flow state was achieved in both groups at the Magnet_2 stage, with statistically significant differences in favor of the experimental group. Magnet_2 presented educational content through textual information and participants had to solve a problem related to that content; its AR version offered the possibility to experiment with the magnetic fields. The main differences between the Magnet_2 stage with the first and the last stages are described as follows: (1) Magnet_2 introduced new content; (2) it dealt with a moderate challenge; and (3) it helped students by providing interactive activities. Those findings, support the Pearce at al.'s work (2005) where they remark the importance of analyze the flow as a process rather than a just an overall state, useful information can be gather from this measure approach. In this regard, from the results observed we conclude that students enjoyed interacting with objects and visualizing digital information associated with the real objects in tasks that where achievable for them but not extremely easy. Thus, learning designers should strike a careful balance between AR support and task challenge. The textual information, necessary to guide and provide educational content, sometimes acted as an intrusive component in the visual and tactile media used. Therefore, it is necessary to find out in which situations it is beneficial to integrate textual information in AR-based learning activities and identify effective ways to incorporate the information in this new media.

Regarding the learning effectiveness of both applications, after conducting a statistical analysis on the pre- and posttest scores, it was found that students who used the AR application performed significantly better on knowledge than those who were taught using the web-based application. Those findings seem to support the outcomes of research studies (Andujar, Mejias, & Marquez, 2011; Chen, Chi, Hung, & Kang, 2011; Kamarainen et al., 2013; Kaufmann & Schmalstieg, 2003; Lin, Duh, Li, Wang, & Tsai, 2013), which showed that AR technology contributed to improve academic achievement compared to traditional teaching methods. Moreover, it was found that the experimental group showed better results on visualization-related questions than students in the control group. The AR-based application enabled students to experiment interactively with electric and magnetic fields as well as to observe the effect of magnetic forces on their circuit. It provided instant and reliable feedback. Therefore, the AR-based application gave students the opportunity to try and observe different options instantly, whereas the web-based application did not offer students any possibility to experiment. A possible explanation of the effectiveness of the AR-application over the web-based application might be associated with either the concentration, control, autotelic levels achieved, or the differences in cognitive effort required to handle the abstract concepts involved. The control group participants required a higher cognitive effort to learn and solve problems that required visualization whereas the experimental group had better opportunities to understand the combined behavior of electromagnetic forces. The findings of the current study extend those of Dori et al. (2007) who found that students improved learning outcomes through the use of visualization in a web-based course. Further studies with a larger data sample are necessary to identify the causes of learning effectiveness of the AR-based application over the web-based application.

Some limitations of the study need to be pointed out. First, it involved short-term retention of the basic principles of electromagnetism; it is likely that a long-term retention evaluation would have provided more insight into the effectiveness of the AR application in high school students. Restrictions in the time tables of the high schools involved compelled us to conduct these short-term interventions. Second, although both groups used tablets to interact with the learning environment, the novelty factor of augmented reality could act as a disturbing factor. Thus, further studies are necessary to diminish the novelty factor introduced by augmented reality technology. Third, data collected were self reported.

Our findings seem to support the outcomes of prior studies (Bujak et al., 2013; Dunleavy et al., 2009; Kye & Kim, 2008) which showed that AR-based applications contributed to increased academic achievement and promoted positive emotional experiences compared to traditional teaching in STEM fields (science, technology, engineering, and mathematics). However, the findings of this study went further, suggesting stronger indicators in favor of the use of AR applications for learning. Indeed, the AR-based applicationwas not compared to traditional teaching but to another appealing form of ICT-based learning. Furthermore, both the control and experimental groups used the same kind of handheld device, making both groups similarly vulnerable to the novelty effect caused by the use of tablets for a learning activity. Finally, it is worth highlighting that participants were high school students, who are typically harder to engage and motivate than children (Martin, 2012).

Based on the results of this study, it can be concluded that the AR-based application was more effective than the web-based application in both promoting students' knowledge of the basic principles of electromagnetism and in fostering flow experiences. Therefore, augmented reality applications can be used as effective learning tools within high school electromagnetic courses.

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