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A Learning Experience in Inquiry-Based Physics with Immersive Virtual Reality: Student Perceptions and an Interaction Effect Between Conceptual Gains and Attitudinal Profiles

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Abstract

The integration of immersive virtual reality (VR) in authentic science classrooms can result in a totally new learning experience for the students. However, the effect of such a learning experience on students' conceptual learning gains and their perceptions of the experience, while considering students' pre-existing science- and digital technologies-related attitudinal profiles, has not been explored to date. In this study, we have enacted a 90-min technology-enhanced inquiry-based intervention with high-school students ($n=107$), on the topic of the Special Theory of Relativity in a Physics course, using a learning experience design, structured around an immersive VR simulation. Firstly, we aimed at examining students' attitudinal profiles and, secondly, at exploring the potential differences of those profiles in relation to conceptual learning gains and perceptions of the learning experience. A clustering analysis has revealed two attitudinal profiles: the *low-attitudes profile* ($n=48$) included students with low science- and digital technologies-related attitudes, and the opposite for the *high-attitudes profile* ($n=59$). Results from a 2×2 RM ANOVA indicated a statistically significant interaction between conceptual learning gains and attitudinal profiles. In addition, a one-way MANOVA test showed statistically significant differences between the two profiles in relation to students' perceptions of the learning experience, with the students of the high-attitude profile outperforming their counterparts. We discuss our findings, focusing on the implications of students' individual differences in learning and attitudes linked to the integration of immersive VR in inquiry-based instruction.

Keywords Immersive virtual reality (VR) · Technology integration · Learning experience · Digital technologies attitudes · Scientific attitudes · Physics education

Introduction

Emerging technologies have the potential to support educational reforms and to enhance teaching and learning practices (Elstad, 2016), including teaching, and learning in science (Aina, 2013; McFarlane & Sakellariou, 2002). Especially in the science and physics education field, emerging technologies, such as immersive Virtual Reality (VR) simulations, may facilitate the teaching and learning of physical concepts and phenomena (Barab et al., 2000; Pirker et al., 2012, 2013), which cannot directly be observed through daily experiences (e.g. the special theory of relativity—STR) (Arriassecq & Greca, 2012; Carr & Bossomaier, 2011). In addition, immersive VR simulations can engage the learners in a virtual world, in which they can conduct simulated experiments, and to visualize their effects in a 3D virtual environment (Bogusevschi et al., 2020). Taking into account that epistemological mechanisms, such as mental imagery and thought experiments, are central in physics learning (Botzer & Reiner, 2005), immersive VR constitutes a considerable medium, through which those mechanisms can be supported.

Research work on VR in education has been undertaken over the past decade, with a predominance of empirical

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studies that have been conducted in science and mathematics education (Hew & Cheung, 2010; Mikropoulos & Natsis, 2011). However, previous work has primarily focused on non-immersive VR, delivered via desktop computers. The recent commercial availability of high-end immersive VR (i.e. HTC Vive, Oculus Rift) and the fact that an increased number of young children is nowadays experiencing immersive VR as part of leisure time (Southgate et al., 2019) lead to an anticipated integration of immersive VR simulations in real classroom settings.

Immersive VR simulations through head-mounted displays (HMDs) currently comprise innovative additions to science teaching and learning, offering a broader repertoire of learning opportunities. For instance, a clear advantage of HMDs is their ability to create 3D stereoscopic (as compared to 2D or monoscopic) displays, thus mimicking interactions (Hite et al., 2019). In this way, immersive VR simulations could complement paper-and-pencil activities in supporting students' understanding of complex scientific theories, such as the STR, which is the focus of the present study, due to their affordances for interactive visualizations (Belloni et al., 2004; Carr & Bossomaier, 2011). Moreover, immersive VR simulations could facilitate students' understanding of abstract scientific phenomena due to their potentiality to foster an active environment, which can increase students' engagement with the learning content (Jambi et al., 2019). From a theoretical point of view, Winn (1993) argued that VR simulations have an added value when integrated within constructivist approaches, since students construct their learning through relating their reflections about the simulated objects in the virtual environment to previously learnt abstract concepts (Winn, 1993). Especially in STR instructions, immersive VR simulations can provide significant aids towards this direction.

However, the meaningful and effective technology integration of immersive applications in authentic educational contexts comes along with great challenges (Georgiou et al., 2019, 2020; Ioannou et al., 2020; Georgiou & Ioannou, 2021). As argued by Jowallah et al. (2018), when it comes to the integration of immersive VR simulations in schools, it is imperative to take into consideration the fusion of technology and pedagogy, aiming to result in learning experiences that can leverage the affordances of VR within K-12 education. As part of the broad research line of emerging technology integration in schools, different factors, which may ensure effective uses of technology in schools, have been already investigated (Howard et al., 2015; Lai & Bower, 2019). For instance, a large body of research has focused on how teachers' individual beliefs and pedagogies (Hennessy et al., 2005; Inan & Lowther, 2010; Miranda & Russell, 2012; Prestridge, 2012), teachers' needs and expectations (Georgiou & Ioannou, 2019a), teachers' confidence (Georgiou & Ioannou, 2019b), but also cultural factors (e.g. Goodson et al., 1995; Howard & Maton, 2011) or institutional differences (Perrotta, 2013), may define the success of technology integration. However, research has systematically neglected students, as key stakeholders of any novel technology integration endeavour. On one hand, the evaluation of students' perceptions of the learning experience structured around the integration of emerging technologies in the classroom is deemed crucial, as students' voices could shed light on the learning experience itself (Chang et al., 2015). On the other hand, it is also critical to delve into factors related to students' personal attributes (e.g. attitudes), as those may have a significant effect on how the integration of novel technologies in the classroom is perceived as well as on subsequent conceptual learning. This research gap becomes even more crucial in efforts that aim to situate immersive VR simulations in the context of student-centred pedagogies, e.g. inquiry learning, rather than being used as a stand-alone format (Georgiou et al., 2020).

In this study, we investigate the potential effect that the integration of an immersive VR simulation in inquiry-based physics lessons may have on students' conceptual learning gains and perceptions of the learning experience, considering students' attitudinal profiles as these derive from their scientific- and technology-related attitudes. Even though attitudinal profiles deriving from public attitudes towards science and technology have been already explored (Pullman et al., 2019), to the extent of our knowledge, no previous research has explored pre-existing students' attitudinal profiles, deriving from their scientific- and digital technologies–related attitudes. Moreover, potential differences in students' conceptual learning gains, as well as potential differences in students' perceptions of a learning experience that entails an immersive VR in the classroom, taking their attitudinal profiles into account have not yet been examined. We next elaborate on the conceptualization of the constructs which are examined in this study. In addition, we review empirical and theoretical support for the potential relationships between these attitudinal variables in relation to conceptual learning and students' perceptions of novel technology integration.

Theoretical Background

Technology-Enhanced Inquiry-Based Learning

Inquiry is one of the core scientific practices, and inquiry-based learning constitutes a student-centred approach which allows students to learn about scientific phenomena in an exploratory way resembling authentic scientific practices (National Research Council [NRC], 2012). It can be defined as learning by engaging in authentic scientific research activities such as problem formulation, hypothesis generation, setting up and conducting experiments and drawing conclusions (Chinn & Malhotra, 2002).

Inquiry-based learning has been proven to foster learners' understanding of scientific concepts and phenomena (Schroeder et al., 2007), the acquisition of scientific practices (Bybee, 2011), learners' thinking skills and critical thinking (Haury, 1993), positive attitudes towards science (Shymansky et al., 1983), while also promoting the development of an epistemological awareness of how science operates (Chinn & Malhotra, 2002). Moreover, with the presence of appropriate scaffolding, learners can develop evidence-based reasoning and construct scientific explanations (Kyza et al., 2011).

Even though inquiry as a learning approach has a long history (Dewey, 2018), the past few years' technological developments, such as computer simulations, have been used in learning and instruction for enhancing inquiry learning (De Jong, 2006). Research in the field of technology-supported inquiry learning has shown that digital tools, such as simulations and digital media, have the capacity to built-in support for the processes of inquiry learning (Van Joolingen et al., 2007) and be effective in promoting student learning (e.g. Bell & Trundle, 2008; De Jong, 2006; Lee et al., 2010). For instance, inquiry-based learning in virtual labs can promote students' conceptual understanding of physical phenomena and concepts (e.g. Kollöffel & de Jong, 2013). In particular, virtual experiments add value in inquiry learning by allowing students, among others, to explore unobservable phenomena, such as the STR chosen in this study, and link them to observable phenomena (De Jong et al., 2013).

VR simulations have started receiving increased attention, as means to facilitate students' inquiry-based practices, due to their interactivity and high-fidelity representational properties—the same properties which have made digital visualization a valuable tool for scientific discovery by scientists (Edelson et al., 1999; Kim, 2006; Wu et al., 2019). However, while an increasing corpus of studies has reported on the use of VR simulations in order to engage students with inquiry-based learning (Barab et al., 2000; Hansen et al., 2004; Kim, 2006; Shin, 2002; Wu et al., 2019), what still remains unclear is 'how' VR simulations, and especially immersive VR simulations, should be integrated in the inquiry-based learning process and what are the effects of students' learning experiences—encompassing immersive VR simulations—on their understanding of physical phenomena and concepts. This can be attributed to the fact that immersive VR is a new technology to the classroom and thus, in inquiry-based learning as well (Fegely et al., 2020).

Attitudes

Attitudes have long been recognized as important predictors of individual differences in many educational endeavours. That said, students' attitudes, whether positive or negative, affect how students respond to a given learning environment and its embedded materials (Pyatt & Sims, 2012; Teo, 2008). Attitudes also affect the degree to which the students may show increased attention to classroom instruction and an interest for further studying a specific subject e.g. science (Jarvis & Pell, 2005; Osborne et al., 2003). Provided that in this study we focus on a learning experience encompassing the integration of an immersive VR simulation in an inquiry-based physics lesson (more information is provided in the "Method" section), it becomes apparent that students' science- and digital technologies–related attitudes, become considerable variables to explore.

Science-Related Attitudes

Attitudinal constructs such as students' dispositions in relation to science (Koballa & Crawley, 1985) have been associated with students' actions and behaviour, which are considered precursors to science achievement (Koballa & Glynn, 2007; Sherif et al., 1965). As part of those attitudinal constructs, science-related attitudes have been a focus of study for many educational researchers in science education, since the exploration of aspects that might enhance students' attitudes can lead to potential increased learning gains, science academic achievements (Chen & Chen, 2012; Freedman, 1997; Gardner, 1975; Oliver & Simpson, 1988; Osborne et al., 2003; Özkal, 2007; Weinburgh, 1995; White & Richardson, 1993), interest in science (Jarvis & Pell, 2005) and behavioural intentions, e.g. physics enrolment (Crawley & Black, 1992). In addition, students' science-related attitudes have been proven to comprise predictors of students' conceptual learning in formal and informal educational settings (Newell et al., 2015; Osborne et al., 2003).

A difference between attitudes toward science and scientific attitudes has been crystallized in the literature (Schibeci, 1983). In this respect, science-related attitudes are distinguished in two broad categories: attitudes toward science (e.g. interest in science, attitude toward scientists, attitudes toward social responsibility in science, attitudes to scientific inquiry) and scientific attitudes (e.g. open-mindedness, honesty, scepticism, curiosity) (Gardner, 1975; Osborne et al., 2003). In this study, we focus on the adoption of scientific attitudes by students, which reflect open-mindedness and willingness to revise opinions based on experimentation and empirical data (e.g. 'I am curious about the world in which we live') (Fraser, 1978; Klopfer, 1971).

The adoption of scientific attitudes by students has been proclaimed as a key objective in science education (Rowlands, 1971), especially in response to the so-called Sputnik effect, which sparked a series of implications for curricular objectives (Cohen, 1971). It has been shown, for instance, that learning environments which offer opportunities for students 'to negotiate, to challenge and to question their own ideas, others' ideas or even the teacher's ideas can promote students' epistemological understanding about science' (Tsai, 1998, p. 486), while the latter is associated with the adoption of scientific attitudes (Fulmer, 2014; Özkal, 2007). Scientific attitudes have been also found to be associated with science achievements (Lee, 2004; White & Richardson, 1993), even though such associations were reported as non-significant in a few studies (e.g. Olasehinde & Olatoye, 2014), suggesting the need for further examination of other factors which might hinder science achievement in schools. For example, students' perceptions of the learning environment have been found to be another factor affecting science achievements, also positively associated with students' scientific attitudes (Lee, 2004).

However, despite the great attention that has been given over the last decades on the students' scientific attitudes and their implications, there is a general lack of knowledge on how students' scientific attitudes may be coupled with other personal attributes, e.g. digital technologies-related attitudes, and how those may have an effect on learning experiences involving immersive VR integration in the classroom. Overall, research focusing on the implementation of novel technology integration, and in particular, immersive VR simulations in physics education, is currently in its infancy (Georgiou et al., 2020; Jowallah et al., 2018; Southgate et al., 2019). Considering the immense potential of learning experiences encompassing immersive VR simulations in science learning, it becomes imperative to further explore the potential effect of students' scientific attitudes on their conceptual learning in physics classrooms as well as their perceptions of such learning experiences.

Digital Technologies–Related Attitudes

Gaining an understanding of students' attitudes towards digital technologies (e.g. computers, tablets, virtual worlds, AR, and VR apps) seems to be crucial in efforts to effectively integrate those in instruction. This is essential, as research has already demonstrated that digital technologies–related attitudes can have an impact on user acceptance but also on future behaviours towards technology (Teo, 2006; Teo & Noyes, 2008), such as technology usage (Huang & Liaw, 2005). During the past few years, a considerable body of literature has been devoted, for instance, to describing the relationship between computer attitudes and its associated variables, such as computer use and experience, computer training and instruction (Teo & Noyes, 2008).

Computer attitudes can be defined as dispositions towards computers with respect to learning or using them, while this construct has been found to be a predictor of the adoption of new technologies, such as computers (Myers & Halpin, 2002). Overall, regardless of how sophisticated and capable the technology may be, its effective implementation, let alone effective integration in education, depends upon users having a positive attitude towards it (Huang & Liaw, 2005).

It has been argued that a comprehensive measure of attitudes towards computers should include the measurement of the perceived ease of use, the affect towards digital technologies and the perceived usefulness, as those variables have been reported as essential towards the prediction of secondary students' acceptance in efforts to successfully implementing instructional technology in educational settings (Teo & Noyes, 2008). The foundation of the above-mentioned measurements lies within the framework of assessing computer attitudes, as proposed by Kay (1993), the theory of planned behaviour (Ajzen, 1988) as well as the Technology Acceptance Model (TAM) (Davis et al., 1989), which has evolved during the years (Lee et al., 2003; Legris et al., 2003; Marangunić & Granić, 2015), while also those measurements have been adapted to target secondary-school populations (Teo & Noyes, 2008).

Along these lines, relevant research work has revealed that students' perceptions of utility and enjoyment of certain computing devices are precursors of students' positive attitudes towards science and technology (Sah et al., 2020). However, according to Sah et al. (2020), unexpected research outcomes may occur in the context of pedagogical interventions in which education-specific devices are being used as part of instruction, and specifically, when the intervention is designed for students who are less interested in technologies. The same authors suggest that pre-existing attitudes towards technology may affect the way in which students perceive the technology used in terms of usefulness and enjoyment.

In relation to educational VR technology, research has already shown that students seem to have positive attitudes towards it (Mikropoulos & Natsis, 2011; Mikropoulos et al., 1998), as well as to hold positive perceptions of VR in education (Domingo & Bradley, 2018; Kavanagh et al., 2017). Students' positive attitudes towards VR learning environments have been also reported, not only due to the interest, enjoyment and sense of realism that VR triggers to students, but also due to fact that VR environments facilitate students' understanding of scientific concepts and phenomena (Huang et al., 2010; Shim et al., 2003). However, despite the fact that students' perceptions of multimedia learning environments, such as immersive VR simulations, are considered important and timely (Maor & Fraser, 2005), the effect of digital technology-related attitudes (i.e. perceived ease of use, affect towards digital technologies and perceived usefulness) on students' perceptions towards learning experiences that involve immersive VR simulations remains unexplored. Subsequently, the effect that an inquiry-driven learning experience, that encompasses immersive VR simulations, may have on students' conceptual learning gains, accounting for attitudinal trends, has not yet been examined.

Rationale and Research Questions

Research on the integration of immersive VR simulations in inquiry-based science classroom settings has just started to emerge. Unsurprisingly, the effect of learning experiences structured around immersive VR simulations on conceptual learning gains and students' perceptions of the learning experience, taking into account their pre-existing attitudinal profiles, has not yet been explored. Such an investigation, however, could better inform instructional design efforts involving the integration of immersive VR simulations in inquiry-based science classrooms.

In this study, we have enacted a technology-enhanced inquiry-based intervention with high-school students, on the topic of the special theory of relativity (STR) in a physics course, using a learning experience design, structured around an immersive VR simulation. In this context, we addressed three main research questions, as follows:

1. Are there any attitudinal profiles deriving from students' scientific and digital technologies–related attitudes, prior to the intervention?
2. Are there any statistically significant differences between high-attitude and low-attitude students on their conceptual learning gains on STR, after the enactment of the technology-enhanced inquiry learning experience?
3. Are there any statistically significant differences between high-attitude and low-attitude students on their perceptions of technology-enhanced inquiry learning experience?

Method

Participants

Six different physics classes participated in this study, composed of a total of 107 high-school students (10th–12th graders) of which 50 were girls (47%) and 57 were boys (53%), with a mean age of 15.78 years old (SD = 0.65). The students were guaranteed anonymity as well as that the involvement in the intervention would not contribute to their final physics grade, at the end of the academic year. In addition, consent forms were obtained from the students' legal guardians regarding the data collection before the intervention. The students worked collaboratively in mixed-ability groups of 3–4 members throughout the intervention. However, students completed individually all the tests and the questionnaires, which were administered for data collection purposes. At the outset of the implementation, students were also warned about possible side effects (i.e. motion sickness, nausea, dizziness) and were asked to report immediately any of these effects to the researchers (however, we have not observed these side effects in our study). Last, the students were informed that they were not obliged to engage with immersive VR if they did not wish to do so; in this case, the students could watch the simulation from the external projection and not be immersed (however, all students who participated in this study selected to be engaged and work with the immersive VR).

Learning Material

The STR topic

The learning material focused on one of the most outstanding theories of modern physics—the special theory of relativity (STR)— and followed the inquiry-based pedagogy. The consequences of STR cannot directly be observed through daily experiences (Arriassecq & Greca, 2012), and researchers claim that pencil-and-paper exercises alone are often insufficient to aid student understanding of abstract ideas, such as those in the STR. Therefore, the integration of multimedia, and especially immersive VR in instruction, has the potential to add significantly in the conceptualization of this theory and its implications, due to an advanced level of visualization and interactivity that these media offer to the students in comparison to traditional exercises (Belloni et al., 2004).

Nevertheless, introducing STR into secondary education may entail difficulties, due to the abstract nature of its concepts and its counterintuitive character. Yet, prior research findings have shown that upper secondary education students are able to cope with the basic ideas of the STR, especially when the learning material follows a constructivist approach within which the STR is approached qualitatively, and mathematical formulas are used to a limited degree (Dimitriadi & Halkia, 2012). Moreover, research has shown that both secondary students and university students face difficulties in understanding basic physics concepts which are considered requirements for the STR (e.g. motion, velocity, and frames of reference), with little variation between the two groups (Saltiel & Malgrange, 1980). The above-mentioned arguments have been used towards the selections of the STR as a topic for our intervention. The intervention aimed at promoting students' understanding of the STR implications (i.e. time dilation, length contraction, relative simultaneity), building on the STR axioms.

The learning material developed by Dimitriadi and Halkia (2012) on the topic, which is considered appropriate for secondary education, was carefully examined, and specific tasks were adopted with necessary adaptations applied for the integration of digital technologies (i.e. an immersive VR simulation, a video) in the teaching sequence. The conceptual path chosen is the one that was found to follow most of the scientific books, that is a qualitative approach to the first axiom of the STR, a reference to problems arising at the speed of light which links to the second axiom, followed by an introduction and elaboration of the consequences of the STR accounting the two axioms. No complicated terminology or mathematical formalism was used, except for just one simple application of the Pythagorean theorem with which all the students were already familiar as this had been already taught, as part of the national curriculum.

The pedagogical Approach

The inquiry-based approach was embraced for promoting social construction of knowledge through the enactment of learning activities that involve the development of hypotheses, a data collection and analysis process, followed by data interpretation and debate with peers using evidence and representations towards the formation of coherent and evidence-based arguments (Constantinou et al., 2018; Chinn & Malhotra, 2002). The material was organized into inquiry phases as proposed by Pedaste et al. (2015), including an orientation phase, followed by conceptualization, investigation, conclusions and discussion (Pedaste et al., 2015). In the orientation phase, the students attended a preparatory session for familiarizing themselves with the two axioms of STR and were also introduced to a given mission, which drove the whole intervention. The mission concerned two identical twins, one of whom travels into space with a relativistic speed and the other staying on Earth. For both twins, the initial plan was to meet again, in 10 years' time, after their initial separation to celebrate their 35th birthday together. However, after studying the STR, one of the twins starts to worry, about whether they will manage indeed to celebrate together. The driving question for the students was the following: 'Why do the twins worry about celebrating their 35th birthday together after studying the STR? Collect evidence and develop your own explanation to address the question'. In the conceptualization phase, students were asked to generate a hypothesis and make predictions on the given problem within their groups. During the investigation phase, the students collaboratively analysed and interpreted data within their groups, which were collected from five learning stations. At the end of the intervention, the students drew conclusions, and each group provided a solution to the given mission, which was then discussed and shared on the plenary. A more detailed description of the particular learning activities per inquiry cycle is presented below.

The Learning Activities

A 60-min preparatory session took place prior to the intervention to introduce the given mission and trigger students' interest in the topic. The educational objective of the preparatory session was to guide the students, through simple reasoning to the wording of the two axioms of STR: (i) there is no way that we can understand whether we are motionless or moving at a constant speed; these two situations are equivalent (Axiom 1); (ii) the speed of light is always constant, regardless of the speed at which the light source moves or an observer measuring the speed of light (Axiom 2). In the first task of the preparatory session, students were presented with various snapshots of everyday life and were asked to analyse and interpret them. For instance, a scenario was given in which a train is moving in a straight line and smoothly. Students were asked to respond to a series of questions, related to how a passenger inside the train and an observer outside the train can find ways to define (i) whether they are moving in general (without defining the motion) or (ii) whether they are moving with a uniform motion. In the second task, the students read a narrative about the speed of light and its invariance and were then introduced to a thought experiment; according to the experiment, two observers in a train measure the speed of light both when the train is not moving and when its motion is uniform. Then, the students responded to questions related to the 'measurement' of the speed of light by immobile observers and observers who are moving relative to the source of the light.

The intervention of this study followed this preparatory session and lasted 90 min. During the intervention, the students worked in groups of 3–4 members. First, the students were asked to recall their given mission and were requested to make their initial hypotheses and predictions as well as to report these in a given worksheet. Then, the students proceeded with the investigation phase (i.e. data collection, analysis and interpretation) that was organized in the five learning stations. The stations served as data-collection points during the inquiry learning process; two of the stations utilized an immersive VR simulation, a third station included video material and the other two stations provided textual information.

In the first learning station, the students conducted a thought experiment: 'Einstein's train paradox'. The students watched a film of National Geographic (with subtitles in their native language) in which two observers, moving with respect to each other, observe two lighting strikes. The stationary observer concludes that the two strikes occur simultaneously, whereas the moving observer concludes that they do not. The learning goal was to help the students infer the relativity of the simultaneity of two events (i.e. whether two events are taking place at the same time is relevant) and conclude that 'it is possible that two observers moving

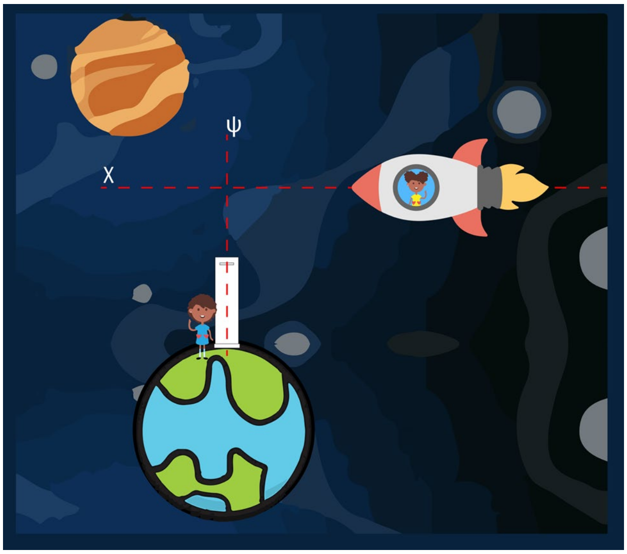


Fig. 1 The thought experiment: ‘light clock’

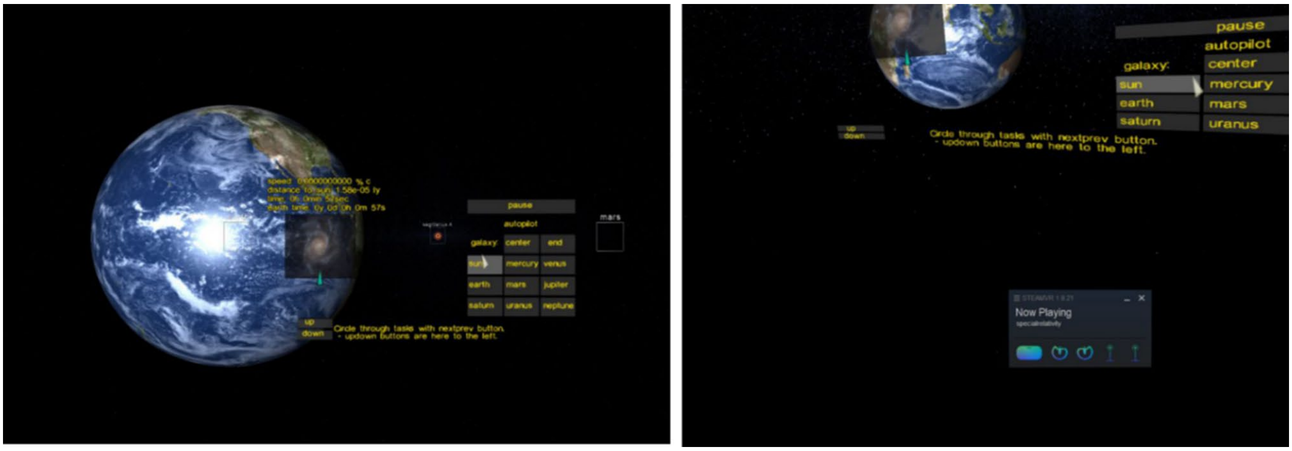
towards each other, can disagree on whether two events are taking place at the same time; both opinions are equivalent.’

In the second station, the students conducted another thought experiment: ‘light clock’. A source of light appears on the earth, as illustrated in Fig. 1. This source emits a flash which reaches a mirror at the ceiling of the train and reflects from it. Two observers—the first one is right next to the clock, and the other one appears in the spaceship, outside earth—measure how long this phenomenon lasts, and they come to different conclusions. With the use of the Pythagorean theorem and the second axiom of STR (invariance of the speed of light), the task aimed to help the students to reach to the conclusion that ‘time is a relative concept; two observers moving relative to each other may disagree when measuring a period of time, but their views are equivalent.’

In the third station, the students used the immersive VR simulation (a snapshot from the VR environment is given in Fig. 2) to travel from the earth to the sun and back, while observing the elapsed times in the spaceship and on Earth, based on the running clock of an inertial observer in one of the two inertial reference systems. Students were allowed to further experiment and manipulate the following variables: starting point, travel destination (e.g. from the earth to the centre of the milky way galaxy or other planets) and speed of travel. While running the simulation, the students could observe the two running clocks, as mentioned above, and record the data on their worksheet, as well as the target distance. The students could further interpret the data in group discussions. The different operating rates of the two clocks in the immersive VR simulation triggered further students’ perceptions about time and whether the time is absolute. The aim of this task was the same as in the previous station.

In the fourth station, the students were introduced to another thought experiment: ‘Measurement of a spaceship’s length’. As illustrated in Fig. 3, two observers moving with respect to each other arrive at different measurements about a spaceship’s length. Applying the second axiom, the students inquired about the length of the spaceship from the perspective of the one observer, accounting on the relativity of time. The aim of this task was to help them conclude that length is a relative concept and that ‘two observers moving relative to each other may disagree when measuring the length of an object, but their opinions are equivalent’.

In the fifth station, the students were asked to make a proximity flight towards the Sun via the immersive VR simulation, getting close and passing by it, in order to observe the ‘length contraction’ of a spherical item in the direction of the movement (snapshot of the VR environment presented in Fig. 4). Students were allowed to further experiment and manipulate the following variables: starting point, travel destination (e.g. from any


distance to sun: 1.58e-05 ly
earth time: 0y 0d 0h 0m 57s

Circle through tasks with nextprev button.
- updown buttons are here to the left.

Fig. 2 Snapshot from the VR environment while studying time dilation: travelling from the earth to sun and back

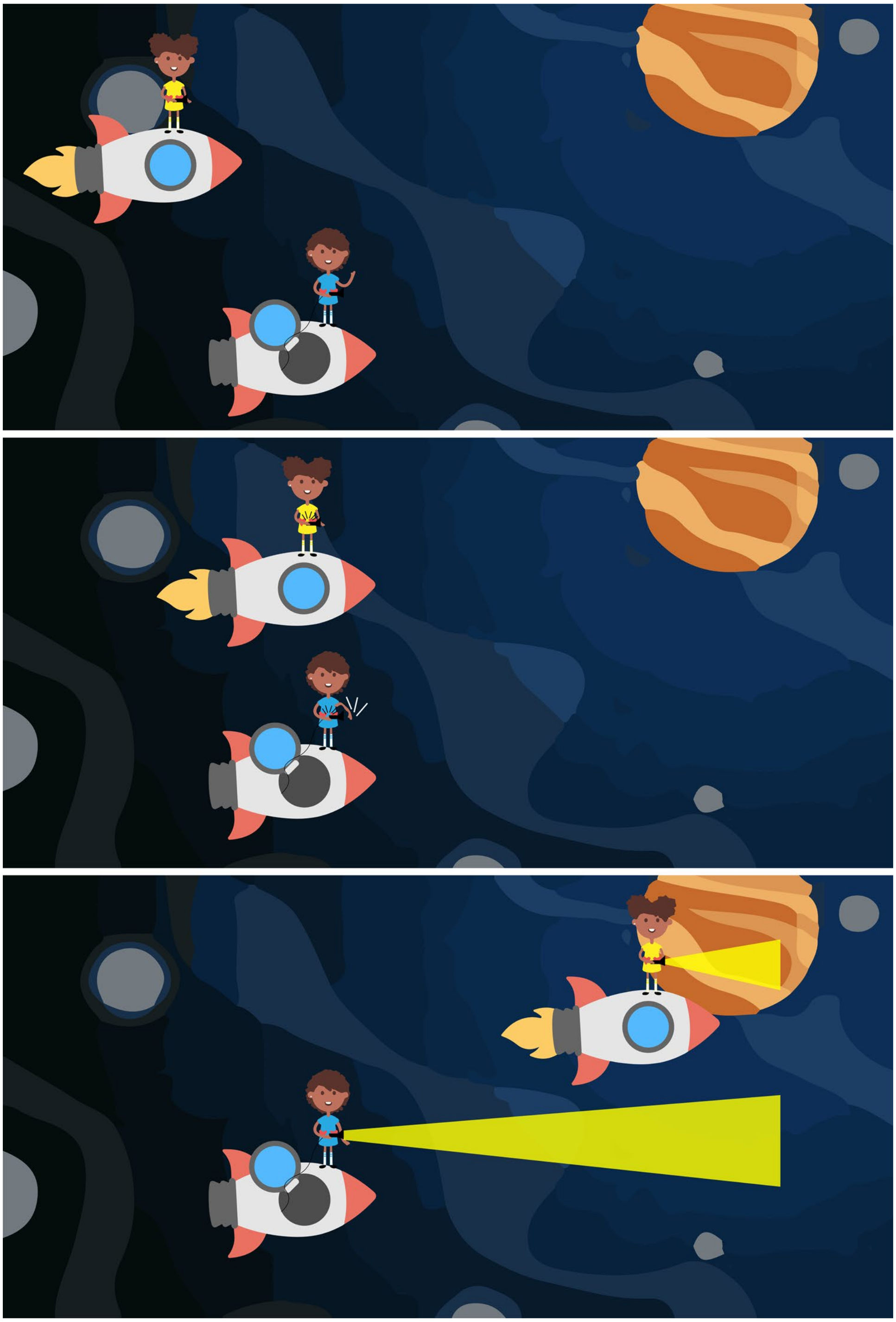


Fig. 3 The thought experiment: 'measurement of a spaceship's length'

planet to another) and speed of travel. While running the simulation, the students could observe the length contraction effect on the basis of their manipulations and in a fully immersive environment. The students could further interpret the data in group discussions. In this way, as argued by Mikropoulos and Natsis (2011), the immersive VR simulation meant to extend students' capabilities to observe physical phenomena, which were beyond the range of their senses. The aim of the task provided in this station was the same as in the previous station.

As part of stations 3 and 5 described above, students within groups had the opportunity to use the immersive VR simulation in turns. However, while only one student could wear a headset at a given time, the others could still

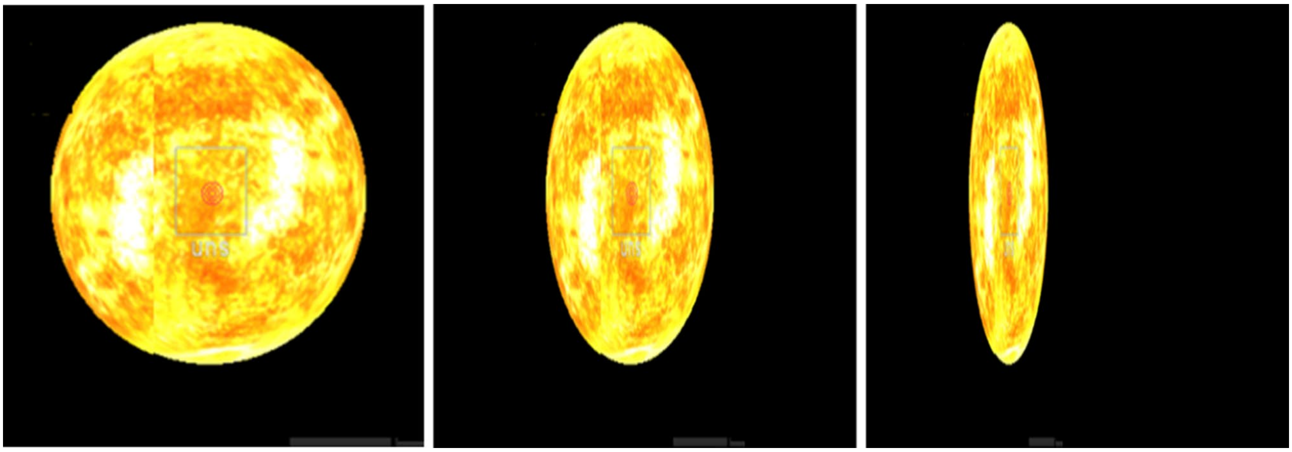


Fig. 4 Snapshot from the VR environment while studying length contraction: proximity flight towards the sun

contribute to the discussion, as the visualizations in the immersive VR simulation were also projected onto an external screen of a laptop computer.

Apparatus

The immersive VR simulation that was used in this study aimed at supporting students' understanding of time dilation and length contraction, as the main STR implications. While using the VR simulation, the students were asked to control a spaceship to travel inside and outside our solar system. The spaceship cockpit was composed of several panels, which provided valuable information, including the distance to a selected destination measured in light-years (ly), the traveller's speed as a factor percentage of the speed of light, the elapsed time in the spaceship and the elapsed time on Earth, from the perspective of an inertial observer. The location of the spaceship was presented by a map displayed on the left, while a set of autopilot controls appeared on the right side of the screen allowing the students to travel to any of the provided destinations (i.e. the sun, all solar planets, outermost bounds). Alternatively, the students could navigate manually

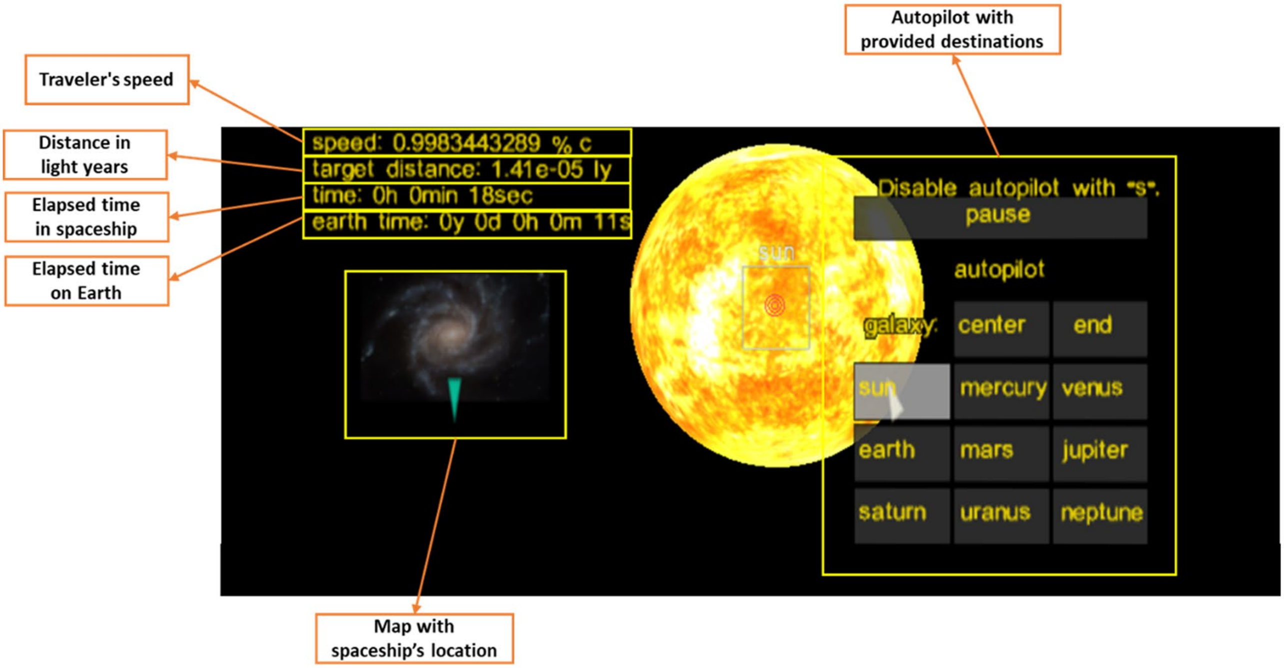

speed: 0.9983443289 % c
target distance: 1.41e-05 ly
time: 0h 0min 18sec
earth time: 0y 0d 0h 0m 11s
Disable autopilot with "s".

Fig. 5 Main screen of the immersive VR simulation with its main characteristics by using the WASD keys on the keyboard (W = accelerate, S = stop, A/D = rotate left/right). Figure 5 illustrates the main screen of the immersive VR simulation with its main characteristics, as presented above.

The particular VR simulation was created by Chu et al. (2019) and was based on a running model developed in C + +, while OpenGL was chosen for the graphics programming and OpenVR to access the HMDs. The physical magnitudes were properly simulated with the aid of a self-written graphic engine specifically designed for displaying objects with massive size differences. The deployment of the immersive VR simulation was enacted with the use of Oculus Rift HMD tethered to personal computers (four sets in total) and equipped with sensors to track the position of the user. This setting allowed a better processing of graphics for real-time tracking and interactions and secured a high-quality learning experience for the students.

This immersive VR simulation was selected due to its technological characteristics and resulting learning affordances. First, the VR simulation is highly immersive, in the sense that it could deliver extensive (i.e. multimodality sensory stimuli), surrounding (i.e. omnidirectional stimuli), inclusive (i.e. no external stimuli from the physical environment), vivid (i.e. richness of sensory information including visual, auditory information and proprioception) and matching (i.e. user movement and system information match) experiences to the students. The immersive characteristics of the VR simulation supported the sense of presence that students could feel within the virtual environment and provided 'first-order experiences' to the students, which are of major importance in the learning process (Mikropoulos & Natsis, 2011; Winn & Windschitl, 2000). Previous work of Chu et al. (2019) has shown that the visualization of the STR consequences in this specific simulation led to high immersion of the participants and increased their knowledge about the STR, while immersive VR simulations have been proven to enhance users' learning in general (Dede, 2009). Second, in comparison to prior simulations on the topic (e.g. Belloni et al., 2004; Horwitz et al., 1994; Carr et al., 2007; Taylor, 1989; Weiskopf et al., 2006), the selected VR simulation provides an interactive real-time and real-scale environment for students to conceive the magnitude and the large-scale effects of STR (Chu et al., 2019). The simulation includes, for instance, both smaller stellar structures (such as our solar system) and larger stellar structures (such as galaxies), allowing students to explore the Milky Way with its diameter of 100,000 light years. This is of great importance, given that the simulation can visualize the length contraction (aka Lorentz effect which flattens the whole universe) by 'making it possible to traverse through the galaxy within seconds, depending on the speed' due to the number and density of stars in our galaxy (Chu et al., 2019, p. 18). Students were also able to teleport instantly to new locations within and across the smaller and larger stellar structures. Consequently, the specific VR simulation could enable 'transduction' as the students were able to feel and experience situations (i.e. travelling with a speed close to the speed of light, STR implications) which would not normally be accessible in the real world. Third, the use of the Oculus Rift HMD along with a sophisticated body tracking system and controller device for interactions provided a high degree of agency and autonomy for the students to control their navigation and interactions within the 3D VR environment.

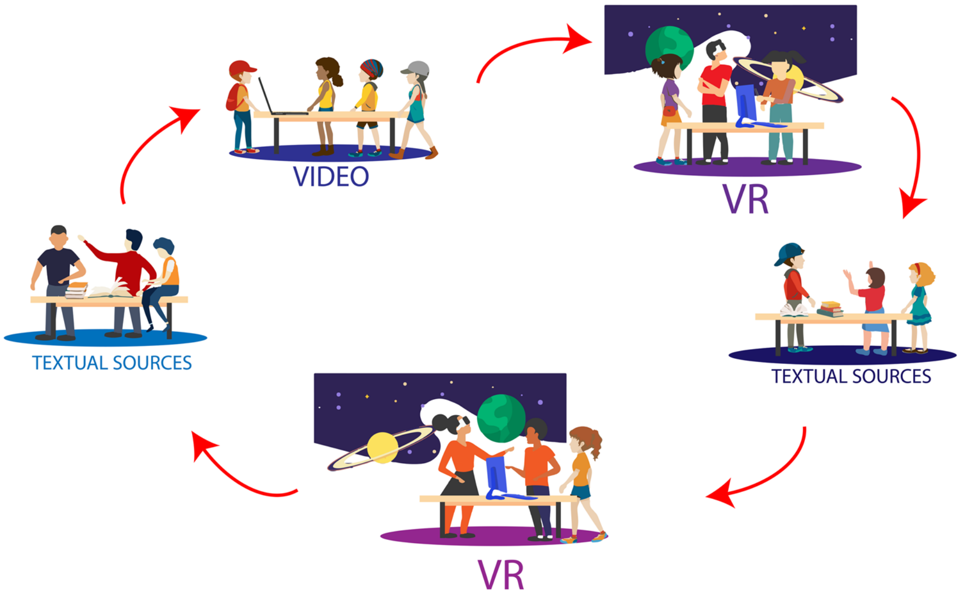


Fig. 6 Classroom setup in learning stations

Procedure

At the beginning of the intervention, all students completed a pre-survey and a pre-conceptual test, during a time slot of 20 min. Then, the 60-min preparatory session took place, in which the students were introduced to the given mission and the two axioms of STR through simple examples and thought experiments (more details are given in 'Learning material' and apparatus). The preparatory session was followed by the 90-min intervention during which the students started studying the learning material within their groups for completing the mission. Specifically, the students were split into five groups, and, through rotation, each group was given 15 min to implement a given task per learning station. Students' transition from station to station was enacted by a bell ringed. In this way, every group could experience all five stations (see Fig. 6).

The learning stations were conceptually connected, as the inquiry-based activities built on each other to promote learning. At the same time, each station could operate independently, as there was not any required sequential order to be followed by the students. In all the stations, students were asked to analyse, interpret and synthesize the pieces of information collected, to explore consequences of the STR (i.e. time dilation, length contraction, simultaneity). In this context, the completion of worksheets was also part of the intervention, to support students in reporting, synthesizing and reflecting on the data collected from the learning stations. In particular, each group was provided with a single worksheet, containing the tasks of the five learning stations. The students in each group were requested to collaborate and work together in completing the worksheet, upon interpreting together the gathered data in each learning station and reaching consensus on their conclusions. In each station, one student per group was assigned as the leader, being responsible to coordinate the group discussions and report the group's conclusions in the given worksheet. The group leader role was reassigned to another student from one station to the next, securing in this manner that all students in a group would enact the role of the leader at least once during the whole intervention.

As soon as the students had passed through all the stations, they were given 15 min to take an evidence-based position as a group to the driving question of this inquiry and discuss their conclusion on the plenary. The intervention was supported by the two first authors with prior extensive science teaching experience and who attended preparatory meetings before each classroom session. Aligned with the inquiry-based approach, the role of the two teachers shifted from the 'dispensers of knowledge' to becoming facilitators for supporting students' learning throughout the process (Anderson, 2002). Towards this direction, the learning material included one checkpoint at the end of each task, in which students were prompted to briefly discuss with the teacher(s) their outcomes and resolve any potential difficulties. Finally, at the end of the intervention, the students were asked to complete a post-conceptual test, as well as a post-activity questionnaire on their perceptions of the learning experience, during a time slot of 20 min.

Data Collection

This study followed a quantitative approach. The data sources included a pre-survey, a pre-post conceptual test and a post-activity questionnaire on students' perceptions of the learning experience. Each one of the data collection instruments is presented below.

Pre-survey

The pre-survey consisted of three parts: demographics, scientific attitudes and attitudes towards digital technologies. Scientific attitudes were measured using the '*Adoption of scientific attitudes*' scale comprised from 5 Likert-style items (e.g. 'I am curious about the world in which we live'), which derived from the *Test of Science-Related Attitudes* (TOSRA) (Fraser, 1978), a valid and reliable instrument. Cronbach's alpha for this scale, as documented by Fraser (1978), was calculated to 0.75. The scale's items were translated into students' native language and cross checked with an expert for face validity. Cronbach's alpha was calculated to 0.78 possessing satisfactory internal consistency of the items.

Students' attitudes towards digital technologies were investigated using a slight adaptation of the *Computer Attitude Measure for Young Students* (CAMYS) (Teo & Noyes, 2008). CAMYS was originally developed to investigate students' attitudes towards the use of computers, using 12 items on a 5-point Likert scale (i.e. '1': completely disagree, '5': completely agree). In particular, CAMYS assesses students' attitudes on three scales: (i) perceived ease of use, (ii) affect towards computers and (iii) perceived usefulness of computers. However, given that as part of this study we were interested in investigating students' attitudes towards digital technologies in general, all the items were adjusted by replacing the term 'computers' with the term 'digital technologies' (e.g. 'I use digital technologies to help me to do my work better') and translated into students' native language and cross checked with an expert for face validity. The items of this questionnaire were deemed necessary for tackling the

Table 1 The scoring rubric that was used for the evaluation of students' responses on the three open-ended questions

Approach	Criteria	Examples of students' responses			Points assigned
		Q1 (time dilation)	Q2 (length contraction)	Q3 (simultaneity)	(max = 10 per question)
A non-relativistic approach	A valid response	It is logical as in the experiments there might be an error factor which significantly affects the measurement	Yes, it is possible due to errors in the measurement and experimentation	It can happen that two observers perceive differently whether two events are simultaneous or not, due to measurement errors or human factors	1.0
	A valid justification	Due to a reaction error, two observers may have found different results due to the human reaction time error for setting up their instruments (chronometer)	It is possible since the two observers may be measuring from a different angle so there can be an error in the measurement. Also, if they measured the object with an instrument of a different degree of accuracy, then they could have different results due to the difference of significant digits. And there is also the instrument error	For instance, they might have different reflexes when observing two events and cannot really distinguish whether those are simultaneous or not. Also, they might have started their clocks at different times of few seconds when measuring the star and end point of an event	1.5
A relativistic approach	A valid response	Yes, time is a relative concept according to STR	Yes, because according to the STR, there is length contraction	According to STR and the consequences of the two axioms that we have studied, it is possible that this can happen	2.5
	A valid justification	Because the two observers have a different reference system, and they move relatively, so they observe things differently. For instance, in the example of the light beam which serves as a clock, the standing still observer sees the beam of the moving observer traveling in a larger distance, but since the speed of light is constant, we can conclude that the standing still observer sees the clock of the moving observer running slower in relation to its own clock. And vice versa	When the two observers use different reference systems, and the one is moving to the other with very high speeds, close to the speed of light, then they will come up with different measurements of the length, in the direction of movement, as a result of the second axiom	Because since time is a relativist concept, if one is in motion and the other is standing still, they may have observed the two events differently, and therefore, they might disagree on whether two facts are simultaneous or not. Both observers will be right	5.0

aims of this study, assuming that understanding students' attitudes towards the use of digital technologies would allow us to better understand their behaviour during the intervention. We then collectively summed the 12-item scores thus creating a higher-order variable for further analysis, reflecting one's own digital technologies–related attitudes, as this is also proposed by Teo and Noyes (2008). The Cronbach's alpha coefficients, as documented by Teo and Noyes (2008), for the three scales were calculated to 0.64 for 'Perceived ease of use', to 0.81 for 'Affect' and to 0.74 for 'Perceived usefulness'. Since the items were translated, and the word 'computer' was replaced with the word digital technologies as mentioned above, we recalculated the alpha coefficients for the three scales, which were found to be 0.86 for Perceived ease of use, to 0.89 for Affect and 0.78 for Perceived usefulness, which are considered as satisfactory.

Pre-Post Conceptual Test

The pre-post conceptual test aimed to assess any differences in students' conceptual learning on the implications of the STR. The test consisted of three open-ended questions, investigating students' understanding of time dilation (i.e. Q1: *If two people measure the duration of a phenomenon, is there a chance they will disagree with their measurements? Explain.*), length contraction (i.e. Q2: *If two people measure the length of an object, is there a chance they will disagree with their measurements? Explain.*) and simultaneity (i.e. Q3: *Is it possible for two people to disagree on whether two things are happening at the same time? Explain.*), respectively.

A scoring rubric was developed to evaluate students' responses on the three open-ended questions. It was observed that the open-ended questions provided to the students could be perceived in a different manner by them, that is, with an either non-relativistic approach (e.g. if two people measure the length of an object, it is possible to disagree with their measurements due to measurement errors in the use of different instruments or units of measurement by observers, etc.), or relativistic approach (e.g. if two people measure the length of an object, it is possible to disagree with their measurements if they make their observations from two different inertial reference systems). Non-relativist responses were expected as it has been confirmed by previous researchers that pre-Galilean notions dominate students' ideas about such concepts (Dimitriadi & Halkia, 2012). Accounting on this observation, the rubric that was developed for the analysis of students' responses in the pre- and post-conceptual test contained both approaches (see Table 1). However, the points assigned to each approach (relativistic vs non-relativistic) were weighted differently so as to provide a lead in the type of responses that are consistent with learning objectives of this intervention. When students provided no response or a totally irrelevant and invalid response that was scored with zero points, whilst the maximum possible score was 30 points.

The rubric was evaluated by the first author of this paper and an independent physicist for securing the validity of the assessment. Inter-rater reliability values (Cohen's Kappa), for all the aforementioned coding processes, were found to exceed 0.85 in every case.

Perceptions of the Learning Environment Questionnaire

As part of the post-activity questionnaire, students' perceptions of the technology-enhanced learning environment were investigated using a slight adaptation of the *Constructivist Multimedia Learning Environment Survey* (CMLES) (Maor & Fraser, 2005). Students were allocated 20 min to complete the survey, after the end of the intervention. CMLES was originally developed to investigate students' perceptions of the learning environment when multimedia programs and constructivist pedagogy are employed. CMLES assesses perceptions on two dimensions: (i) perceptions of multimedia, which cover the subscales of '*relevance*', '*complexity*' and '*challenge*', as well as (ii) perceptions of the constructivist learning process, which cover the subscales of '*negotiation*', '*inquiry learning*' and '*reflective thinking*'. Each of the six subscales is composed of five items ranked on a 5-point Likert scale

Table 2 Results of the K-means clustering of the students based on their attitudes

Variables	Low attitudes profile ($n = 48$)		High attitudes profile ($n = 59$)		F
	Mean value	SD	Mean value	SD	
Science-related attitudes	3.62	0.53	4.37	0.39	69.059***
Digital technologies-related attitudes	3.86	0.51	4.65	0.28	101.448***

ns non-significant

$^{*}p < 0.05$; $^{**}p < 0.01$; $^{***}p < 0.001$

Table 3 Results of the repeated-measures ANOVA

Variables	Low-attitudes cluster ($n = 48$)		High-attitudes cluster ($n = 59$)		F	η_G^2
	Mean value	SD	Mean value	SD		
Pre-test	7.66	3.63	8.96	3.76	11.572***	0.12
Post-test	10.63	5.23	15.51	6.61		

ns non-significant

$^{*}p < 0{,}05$; $^{**}p < 0{,}01$; $^{***}p < 0{,}001$

(i.e. 1: completely disagree, 5: completely agree). As the focus of this study was on the integration of a VR simulation in a constructivist classroom (i.e. inquiry-based learning), the items were adjusted by replacing the term 'multimedia' with the term VR simulation (e.g. Working with the VR simulation, I find that it is easy to navigate). All the items were then translated into students' native language and cross checked with an expert for face validity. Cronbach's alphas for the six subscales, as documented by Maor and Fraser (2005), are satisfactory (ranging from 0.83 to 0.90). Yet, we proceeded with a recalculation of the alpha coefficients, since the items were translated, and certain words were replaced in order to adjust the scale into the study's objectives. Cronbach's alpha coefficients for each subscale were calculated accordingly to α = 0.59 (relevance), α = 0.81 (complexity), α = 0.77 (challenge), α = 0.73 (negotiation), α = 0.75 (inquiry learning), and α = 0.82 (reflective thinking). The results suggest that all CMLES sub-scales used in this study possess satisfactory internal consistency, except relevance (α = 0.59) which appears to have a weak but still acceptable internal consistency.

Analysis and Results

Pre-intervention High-School Students' Attitudinal Profiles (RQ1)

To explore RQ1, we employed a K-means clustering analysis, as a particular modelling technique of finding homogeneous groups based on similarity and/or difference of the objects (Scott & Knott, 1974). The K-means clustering analysis was conducted, setting as attributes students' science- and digital technologies–related attitudes. Given that there is a need to identify the most suitable number of clusters to perform the K-means algorithm, the appropriate number of clusters was decided by parameter exploration. The criteria for the selection of the clusters' number were the smallest distance between the features in the same cluster, as well as the largest distance between the features in different clusters.

The K-means classification analysis provided two clusters, which had statistically significant differences in relation to science-related attitudes (F = 69.059, $p < 0.001$) and attitudes towards digital technologies (F = 101.448, $p < 0.001$). The first cluster included students ($n = 48$)

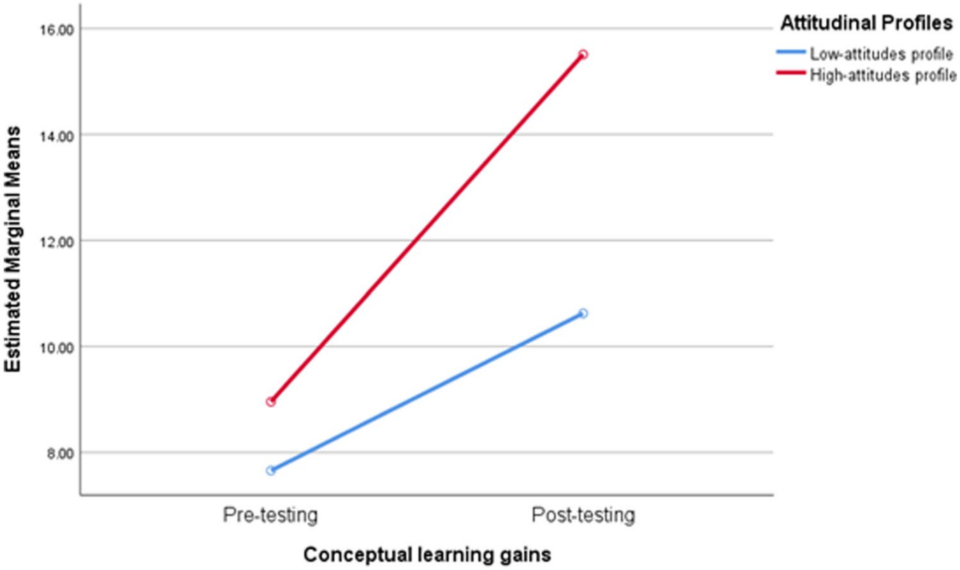


Fig. 7 Statistically significant interaction: conceptual learning × attitudinal profile

Table 4 Results of the one-way MANOVA test on the CMLES Scales

Variables	Low-attitudes profile ($n=48$)		High-attitudes profile ($n=59$)		F	*partial* η^2
	Mean value	SD	Mean value	SD		
Challenge	4.221	0.068	4.458	0.061	6.664^{*}	*0.060*
Complexity	4.288	0.072	4.593	0.065	9.963^{**}	*0.087*
Relevance	4.100	0.065	4.278	0.059	4.152^{*}	*0.038*
Reflective thinking	4.092	0.079	4.342	0.072	5.500^{*}	*0.050*
Inquiry learning	4.217	0.064	4.566	0.057	16.570^{***}	*0.136*
Negotiation	4.438	0.064	4.614	0.058	4.198^{*}	*0.038*

ns non-significant

$^{*}p<0{,}05$; $^{**}p<0{,}01$; $^{***}p<0{,}001$

with low science-related (m = 3.62, SD = 0.53) and digital technologies–related (m = 3.86, SD = 0.51) attitudes, thereby named as '*Low-attitudes*' profile, whereas the second cluster included students ($n=59$) with high attitudes in both variables (science-related: m = 4.37, SD = 0.39; digital technologies-related: m = 4.65, SD = 0.28) (see Table 2), thereby named as '*High-attitudes*' profile.

Differences Among High-Attitude and Low-Attitude Students on their Conceptual Learning Gains on STR (RQ2)

A 2 × 2 repeated measures analysis of variance (RM ANOVA) was conducted to address RQ2. For the testing: (a) the dependent variable was "conceptual learning" as a within-subjects factor with two levels—pre-test and post-test scores and (b) attitudinal profiles were a between-subjects factor with two levels (low-attitudes profile vs. high-attitudes profile). The F-test for any effect was assumed statistically significant when $p<0.05$. In addition, effect size statistics were calculated, with the use of the generalized eta squared (η_G^2) (Bakeman, 2005).

The findings revealed a statistically significant interaction (learning × attitudes profile) (Wilks' Lambda = 0.901, $F_{(1,105)}=11.572$, $p=0.001$), with a large effect size (η_G^2 =0.120), indicating that the students' conceptual learning gains were different for students allocated in the high vs low attitudinal profiles accordingly (Table 3). Specifically, students assigned in the High-attitudes profile (m = 15.50, SD = 6.60) experienced larger gains in the conceptual understanding of STR compared to students allocated in the Low-attitudes profile (m = 10.62, SD = 5.23) (see Fig. 7).

Differences Among High-Attitude and Low-Attitude Students on their Perceptions of the Learning Experience (RQ3)

A one-way multivariate analysis of variance (MANOVA) was performed for RQ3. In particular, as part of this statistical test, we treated students' perceptions as the dependent variable, including all the scales of the CMLES instrument (i.e. challenge, complexity, relevance, reflective thinking, inquiry learning and negotiation) and attitudinal profiles as the categorical independent variable (i.e. low-attitudes profile vs. second-attitudes profile). The criterion of homogeneity of variations was not violated as demonstrated by the F value ($F_{(21,\ 37{,}087)}=0.798$, $p=0.725$). The MANOVA results provided that the value 0.83 of Wilk's Λ is statistically significant, $F_{(6,100)}=3.145$, $p<0.01$, *partial* $\eta^2=0.170$, and therefore, there were differences in students' perceptions of the learning experience, taking their attitudinal profiles into account (i.e. the assumption that the average numbers for the CMLES dependent variables are the same for the two attitudinal profiles is rejected. Further, statistically significant differences have been detected for all dependent variables, after Bonferroni adjustment, setting the p value for each test at 0.083 ($p=0.05/6$). In particular, high-attitudes students outperformed low-attitudes students on *Inquiry learning* $F_{(1,105)}=16.570$, $p<0.001$ with a large effect size (*partial* $\eta^2=0.136$), and *Complexity* $F_{(1,105)}=9.963$, $p=0.002$, *Relevance* $F_{(1,105)}=4.152$, $p=0.044$, *Reflective thinking* $F_{(1,105)}=5.500$, $p=0.021$, *Challenge* $F_{(1,105)}=6.664$, $p=0.011$, and *Negotiation* $F_{(1,105)}=4.198$, $p=0.043$, with medium effect sizes (see Table 4).

Discussion

The discussion of our findings is organized according to the three research questions guiding the study.

Pre-intervention High-School Students' Attitudinal Profiles (RQ1)

The findings revealed that the high-school students who participated in this study were clustered in two different attitudinal profiles: the low-attitudes profile included students with low science- and digital technologies–related attitudes, and the opposite for the high-attitudes profile. This pattern suggests that the higher the students' scores on the scale referring to the adoption of scientific attitudes (i.e. open-mindedness, honesty, scepticism, curiosity) were, the higher the digital technologies–related attitudes (i.e. perceived ease of use, affect towards digital technologies and perceived usefulness) were also observed and vice versa. Attitudinal profiles have been already studied distinguishably for science-related and digital technologies–related attitudes, as well as their association and/or the effect of those on students' performance (Lee, 2004; Shim et al., 2003), and perceptions of particular learning environments (Kavanagh et al., 2017; Lee, 2004). However, attitudinal profiles emerging from both digital technologies-related attitudes and students' adoption of scientific attitudes have not yet been reported in the literature. Their identification and further examination in relation to students' learning experience encompassing novel technology integration in the science classrooms is of paramount importance for research and practice.

Differences Among High-Attitude and Low-Attitude Students on their Conceptual Learning Gains on STR (RQ2)

The 2 × 2 RM ANOVA results demonstrate a within-subjects effect of the enacted intervention, for students' pre-test and post-test scores on their conceptual understanding of the STR. Yet, the effect of students' learning experience on their conceptual learning gains was different for the two attitudinal profiles, thus resulting in statistically significant between-subject effects on students' conceptual learning gains. Coupling with the large effect size reported, the findings imply that the conceptual learning gains are meaningful and result in several implications in terms of instructional design and immersive VR integration in the classroom (LeCroy & Krysik, 2007). More specifically, students with high science- and digital technologies–related attitudes seem to benefit more in terms of their conceptual learning on the STR topic, in the context of the particular learning design that was structured around an immersive VR simulation, compared to the low-attitude students. The findings of this study are in alignment with previously reported research findings, according to which positive associations between science-related (e.g. Lee, 2004) and digital technologies–related attitudes and in particular attitudes towards VR environments (e.g. Huang et al., 2010) have been found with students' conceptual learning gains. However, the significance of examining a combination of attitudinal traits in current efforts of meaningfully integrating immersive VR simulations in the classroom has been highlighted (Jowallah et al., 2018), and our study contributes to this direction.

Overall, the interaction effect between students' learning gains and personal traits, such as attitudes, is evident. Future research efforts, however, could further explore alternative instructional designs that incorporate alternative pedagogies and learning strategies, as suggested by Huang et al. (2010), apart from the inquiry-based approach that was followed in this study, as well as additional attitudinal traits with similar effects.

Differences Among High-Attitude and Low-Attitude Students on their Perceptions of the Learning Experience (RQ3)

Students' positive attitudes towards educational VR technology (Mikropoulos & Natsis, 2011; Mikropoulos et al., 1998) and positive perceptions of VR in education (Kavanagh et al., 2017) have already been reported. However, our findings further add to the existing body of knowledge, by demonstrating an effect that students' attitudes may have on their perceptions of the learning experience. Specifically, our findings have shown that the learning experience, encompassing the immersive VR simulation, was perceived differently by students from the two attitudinal profiles, as designated by the one-way MANOVA statistically significant different mean scores in the CMLES scales. In particular, students of the high-attitudes profile seem to perceive more positively the learning experience, in terms of the immersive VR simulation that was used, as measured by the scales of "challenge", "complexity" and "relevance", in comparison to students of the low-attitudes profile. Likewise, these students seem to perceive more positively the learning experience, in terms of the inquiry-based constructivist learning process that was endorsed, as measured by the "reflective thinking", "inquiry learning" and "negotiation" scales of the CMLES, in relation to their counterparts.

Our findings again bring implications for instructional design and practice, when efforts for integrating immersive VR simulations in instruction are made. As already argued by Huang et al. (2010), crucial factors to be considered during the VR integration in instruction are the appropriateness of such simulations for average learners and the appropriateness of instructional set ups (Burdea & Coiffet, 2003). At the same time, our findings suggest that students' attitudinal profiles should be encountered in efforts of integrating novel technologies into instruction, in addition to the appropriate pedagogy and instructional set up framing such interventions.

Limitations and Future Research

The findings from this study provide empirical support on the interaction effect between students' conceptual learning gains on the STR and their science- and digital technologies–related attitudes. Also, they provide evidence on the effect that students' attitudinal profiles have on their perceptions of a learning experience involving novel technology integration in the classroom. However, this work does not come without limitations. First, even though this study has focused on students' science- and digital technologies–related attitudes, there might exist several other attributes (e.g. other attitudes or skills) that may affect perceptions of the learning experience and conceptual learning gains. Future research should take into consideration the potential effects of other variables, which were not measured in the present study, such as other student characteristics and traits (e.g. inquiry-based skills, collaboration skills or immersive tendencies) on students' perceived learning experiences and conceptual learning gains.

Second, the present study focused on a particular learning design with use of a specific immersive VR simulation, a particular age-range (i.e. high-school students) and a specific domain (i.e. learning in physics). Future studies could replicate this research using different learning-experience designs with other types of immersive VR simulations, as well as focusing on students of different ages and in different domains to examine the consistency of the reported findings in other contexts and settings. Third, this study adopted a quantitative methodology and relied on self-report measures to investigate students' perceptions of the learning experience as well as their conceptual learning gains, which may be regarded as a limitation. Future studies can be also enriched with the collection of qualitative data via observations of the learning process as well as students' interviews on their perceptions, which can be used for triangulation purposes. Fourth, the immersive VR simulation integrated in the instructional design of this study facilitated the investigation phase of the inquiry cycle (Pedaste et al., 2015) and added value to the learning experience by allowing students to explore unobservable phenomena (De Jong et al., 2013). However, future studies in the same direction could further explore 'how' immersive VR simulations should be integrated in other phases of inquiry-based learning cycles and what could be the effects of alternative instructional designs on students' learning gains and their perceptions of the learning experience. Another limitation of our study may relate to the type of students' learning gains, which in this study were limited to students' conceptual learning in physics; future research should also focus on other types of learning outcomes, such as inquiry, and problem-solving skills. Finally, the participating schools were purposively selected (i.e. eager to participate in such an intervention), which limits the generalizability of the findings. Yet, the findings of the study should be transferable to other similar circumstances and contexts.

Conclusions

In response to the educational research focus shift on the integration of immersive VR in authentic educational contexts, in this study, we explored the interaction effect between students' attitudinal profiles and conceptual learning gains, as the latter resulted from students' learning experience with an immersive VR simulation in an inquiry-based teaching sequence. As part of this learning experience, the students were engaged with an inquiry-based learning approach, with a given mission and five learning stations that served as data collection points, involving paper-and-pencil activities, one video activity and the immersive VR simulation in two stations. Also, we investigated the effect of the students' attitudinal profiles on their perceptions of the learning experience. Our findings bring practical implications for instruction. Educators should encounter the potential diversity of student attitudes during the integration of immersive VR simulations in their classrooms for physics learning. Adaptation and personalization to the different needs of students should be catered, as well as the provision of introductory sessions for familiarization with the technology and pedagogy employed in such interventions. Further to that, in this study, students' conceptual learning gains and their perceptions of the learning experience were affected by the particular instructional design and the overall learning experience itself. This leads to implications for technology-supported inquiry-based instructional designs and efforts to integrate novel digital technologies, such as immersive VR simulations, in the classroom. The role of such emerging technologies in instruction should stipulate with the pedagogical approach that is embraced in the classroom, with an evident added value to the learning process. In addition, our findings have implications for teacher training, during which teachers may be guided and supported adequately on how to use immersive VR simulations effectively for teaching and learning in the classroom. We suggest the conduction of further research on novel technologies integration in the classroom, which are grounded on other pedagogies and instructional principles, and on different physics and science concepts as well as the further examination of additional attitudinal traits and their potential effects on students' perceived learning experience and conceptual learning gains.

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Declarations

Ethics Approval All procedures performed involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

Informed Consent Informed consent was obtained from the legal guardians of all the participants.

Conflict of Interest The authors declare no competing interests.

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