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Learning Relative Motion Concepts in Immersive and Non-immersive Virtual Environments

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Abstract The focus of the current study is to understand which unique features of an immersive virtual reality environment have the potential to improve learning relative motion concepts. Thirty-seven undergraduate students learned relative motion concepts using computer simulation either in immersive virtual environment (IVE) or non-immersive desktop virtual environment (DVE) conditions. Our results show that after the simulation activities, both IVE and DVE groups exhibited a significant shift toward a scientific understanding in their conceptual models and epistemological beliefs about the nature of relative motion, and also a significant improvement on relative motion problem-solving tests. In addition, we analyzed students' performance on one-dimensional and two-dimensional questions in the relative motion problem-solving test separately and found that after training in the simulation, the IVE group performed significantly better than the DVE group on solving two-dimensional relative motion problems. We suggest that egocentric encoding of the scene in IVE (where the learner constitutes a part of a scene they are immersed in), as compared to allocentric encoding on a computer screen in DVE (where the learner is looking at the scene from "outside"), is more beneficial than DVE for studying more complex (two-dimensional) relative motion problems. Overall, our findings suggest that such aspects of virtual realities as immersivity, first-hand experience, and the possibility of changing different frames of reference can facilitate understanding abstract scientific phenomena and help in displacing intuitive misconceptions with more accurate mental models.

Keywords Educational technology · Virtual environment · Immersivity · Relative motion

Introduction

Educational research has consistently revealed a poor qualitative understanding of physics among introductory physics and engineering students (e.g., Champagne et al. 1980; Hestenes 1995; Hestenes et al. 1992) and the failure of students to exhibit a significant improvement on physics conceptual evaluation tests after traditional lecture-based instruction (Hestenes 1995; Hestenes et al. 1992). In the area of mechanics, for instance, students have shown a consistent set of difficulties interpreting kinematics graphs (Beichner 1994; McDermott et al. 1987), understanding force and motion concepts (e.g., Trowbridge and McDermott 1981; Thornton 1997), and understanding relative motion concepts (e.g., Metz and Hammer 1993; Monaghan and Clement 1999, 2000). Therefore, the design of effective educational technology tools and instructional methods to facilitate students' conceptual understanding of physics concepts has always been crucially important.

There have been a number of recent research attempts aimed at determining how to use computer-aided instructions to improve students' conceptual and meta-conceptual

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understanding (i.e., explanation of purposes and methods of science). Examples include a Direct Circuit Experiment System for education and entertainment (Hsu 2005), the WEBD project: a research study of new methodologies for a distant-learning 3D system prototype (Cemenasco et al. 2004), Web-controllable scanning electron microscope (SEM) (Chumbley and Chumbley 2007), Sunpath for solar engineering education (Cuevas and Trevisi 2001), and Exploring the Nardoo (Gordon 1996). However, as Seidel and Cox (2003) pointed out, although there is national interest in the potential value of computers in education, the degree of change attributed to computer implementation is significantly lower than anticipated. The majority of educational computer programs created recently have been multimedia programs that combine text, graphics, sounds, and film. According to Cobb et al. (2002), a major criticism of these types of programs is that they mimic resources already existing in schools, such as books, and that "most multimedia programs fail because they add video and graphics to page turning programs." What appears to be lacking in these computer applications is that they do not provide anything of significant value that is additional to already existing educational resources.

Recently, a variety of three-dimensional (3D) immersive simulations have been applied to different educational domains, and in particular to physics education (Barab and Dede 2007; Dede 2000) as an alternative to conventional non-immersive displays. An immersive virtual environment involves a computer simulation of 3D space and a human–computer interaction within that space (Cockayne and Darken 2003). A major characteristics of 3D immersive environments that distinguish them from non-immersive 2D and 3D environments is that they involve egocentric navigation (the learner is surrounded by the environment) rather than exocentric navigation (also referred to as a fishbowl virtual environment) where the learner is outside the environment, looking in (Kozhevnikov and Garcia 2011; Kozhenikov and Dhond 2012). The goal of the present research was to investigate how virtual environments in general and an immersive virtual environment in particular can assist students in learning of relative motion concepts and overcoming their misconceptions.

In the area of relative motion, a variety of students' misconceptions have been documented. Problems on relative motion usually deal with observations (predictions) of an object's motion made by different observers in different frames of reference and then relating these observations to each other. Students do not initially view motion as defined relative to a reference frame, namely that the velocity of the object (its direction of motion and the magnitude of its velocity) depends on the frame of reference of the observer. When presented with simple, one-dimensional, relative motion problems, students exhibited widespread difficulties even after completing a unit of relative motion in their physics class (Monaghan and Clement 1999). Researchers suggested that these misconceptions stem from a lack of experience with frames of references (Monaghan and Clement 2000; Ueno et al. 1992). Most students consider velocity as an intrinsic property of an object that does not depend on the observer's frame of reference. As a result, students do not initially view motion as defined relative to a specific reference frame and frequently do not consider alternative frames of reference besides the default one, which is generally the earth (Camp et al. 1994; Saltiel and Malgrange 1980; Ueno et al. 1992). For instance, Ueno et al. (1992) reported that in ordinary students' discussions, "static ground" is tacitly considered as a "natural" frame of reference. Furthermore, the idea that stillness and motion are not fundamentally different, that is, that the same object can move in one frame of reference and at the same time be stationary in another frame of reference, is particularly counterintuitive (e.g., Camp et al. 1994; Sequeira and Leite 1991). Besides the magnitude of the velocity, the concept that direction of travel is dependent on reference frame is also appears problematic for students (Monaghan and Clement 2000; Saltiel and Malgrange 1980).

A number of researchers have explored the use of instructional approaches including desktop simulations to address difficulties in learning relative motion concepts. Based on the findings that problems involving motion relative to the ground were easier for most students than problems involving motion relative to a river or air, Camp et al. (1994) proposed using a "bridging analogies" problem-solving strategy, according to which the instruction should begin with the easiest cases and then show how more difficult problems are analogous to the easy ones. Several studies using computer simulations on 1D relative motion problems were conducted with the intent of creating a discrepant event in the hopes of producing cognitive dissonance and curiosity. Zietsman and Hewson (1986) used a microcomputer program to diagnose and remediate an alternative conception of velocity. The activities included several different simulated motions of two objects, or cars, moving on a sloping rail from left to right across the screen, and the participants responded by pressing a button when they think the two objects are moving at the same velocity. The researchers showed treatment gains in conceptual understanding of relative motion concepts following learners' use of an extreme case in a desktop computer simulation. Monaghan and Clement (1999) conducted a study with high school post-physics students who interacted with a relative motion computer simulation presented in a predict–observe–explain format. The simulation displayed a 1D relative motion of three objects: a black car, white car, and plane. The black car moved from the far right of the screen to the left, the white car moved from the far left of the screen to the right, and the airplane appeared from the left of the screen and travelled to the right at a higher speed than the white car. During the course of each demonstration, the interviewer ran the simulation once from the ground frame of reference. After the simulation was then reset and run again for several seconds, the interviewer paused the computer simulation and asked the subject to predict the direction and comparative speed of each of the cars when viewed from the airplane frame of reference. Following the student's prediction, the frame of reference was changed to the airplane frame of reference and the remainder of the simulation was presented. After this was done, the researchers interviewed the students on what they had just seen and described instances of successful and unsuccessful mapping of remembered simulation features onto target problems. The researchers suggested that for simulation to be a promising tool to teach relative motion concepts, it should provide an experience that produces dissonance with students' previous experiences and eventually lead to new experiences and formation of a general model that relies on mental simulation rather than computer simulations (Monaghan and Clement 1999). In their other study, Monaghan and Clement (2000) analyzed videotapes of the students, half of which interacted with simulations that provided animated feedback while the other half received numeric feedback. In the animation treatment, students first saw a short (10-s) animation of an event, then the reference frame was then changed (by the interviewer or teacher), and the students predicted the movement direction of the objects relative to the new reference frame. Following their predictions, students saw the animation from the new frame of reference and were then asked to try to explain results that did not match their predictions. In the numeric treatment, students first saw a static graphic on the computer screen, and then, the interviewer (or teacher) double clicked on each of the objects to display numeric velocity data. The reference frame was then changed (by the interviewer or teacher), and the students predicted the numeric speeds of the objects relative to the new reference frame. Following their predictions, the interviewer (or teacher) double clicked on each of the objects to display numeric velocity data relative to the new frame of reference. Students were then asked to try to explain results that did not match their predictions. The researchers provided evidence that both animation and numeric condition students revise their algorithm to develop a correct prediction when confronted with discrepant events. However, in many numeric conditions, students used faulty mechanical algorithms to solve problems, while many animation conditions students used mental imagery to solve problems. The results suggest that computer simulations that facilitate dynamic imagery and produce dissonance with previous experiences might be effective for teaching relative motion. The focus of the current study is to understand the strength and limits of immersive virtual environments as a new media for learning and teaching relative motion concepts. Educational studies have suggested that egocentric, "first-hand" experience in immersive environments can significantly contribute to the sense of "presence" students can feel in virtual environments (Bell and Fogler 1998; Pan and Smith 2008). We expect that the first-person egocentric experiences of switching frames of reference in an immersive virtual environment, where a learner constitutes a part of the scene, will be significantly more effective in promoting students' conceptual understanding of relative motion concepts than conventional desktop simulations, where a learner is looking on the scene from the outside and thus is not able to experience egocentrically how the motion changes from different egocentric viewpoints.

Method

Thirty-seven undergraduate and graduate students (18 females) majoring in different disciplines (engineering, computer science, information technology, and social sciences) from Norfolk State University (VA) and George Mason University (VA) participated in the study. First, the participants were administered a demographic questionnaire, in which they were asked to indicate their age, gender, major, and the number of physics courses they had taken either in high school or at college level (and, in particular, formal courses where the topic of relative motion had been taught).

Participants were randomly assigned to either immersive virtual environment (IVE) or desktop virtual environment (DVE) conditions. There were 19 students (12 females) assigned to IVE conditions and 18 students (6 females) assigned to DVE conditions. All of the students were tested individually. First, each of the participants was pre-tested with the following relative motion assessment battery: (1) an open-ended questionnaire, in which they were asked to explain in their own words in a paragraph or two how they understood the concept of relative motion; (2) an epistemological belief questionnaire, in which they were asked to rate on a 6-point scale their beliefs about the relative nature of motion; and (3) a Relative Motion Problem Solving Questionnaire (RMPSQ) which included sixteen problems designed to assess students' quantitative and qualitative understanding of relative motion concepts.

After pre-tests, all the participants were exposed to either IVE or DVE virtual simulations on relative motion. The activities in the relative motion simulations in general lasted for 25–30 min. After completing these activities, all of the participants were post-tested on the same relative motion assessment battery they were administered on the pre-test. Finally, all of the participants were given a concluding questionnaire, in which they were asked to describe which aspects of the simulation (either IVE or DVE) were particularly helpful for understanding relative motion, as well as to address any difficulties with the simulation and technical problems.

Relative Motion Assessment Battery

The assessment battery consisted of one open-ended question on how they understood the concept of relative motion, an epistemological belief questionnaire, and RMPSQ.

Epistemological Belief Questionnaire

The epistemological belief questionnaire included 5 statements, representing the most resistant students' naïve beliefs about relative motion reported in the literature (Camp et al. 1994; Ueno et al. 1992), such as "Objects which are moving in the real world have one true velocity" or "Relative motion is a perceptual illusion" (see Appendix 1 for the full questionnaire). The students were asked to rate each of the five statements on a scale from "1" (strongly disagree) to "6" (strongly agree). Three statements (1, 2, and 4) are structured so that the higher scoring reflects less agreement with the scientific view and vice versa. As a result, for analysis purposes, the scoring for these items was recoded (inverted) so that the higher scoring reflects more agreement with the scientific view. The reliability of the epistemological belief questionnaire is 0.50.

Relative Motion Problem Solving Questionnaire (RMPSQ)

The RMPSQ included 10 one-dimensional (i.e., two objects are moving along one line or two parallel lines) and 6 two-dimensional (i.e., two objects' trajectories were at 90 degrees to each other) relative motion problems (see Appendix 2). The internal reliability of the questionnaire (alpha Cronbach) is 0.71. The internal reliability of the questionnaire subscales consisting of one-dimensional and two-dimensional problems is 0.67 and 0.57, respectively. The questions were chosen from a number of introductory physics textbooks (Cutnell and Johnson 1995; Halliday et al. 1993) and modified for the purpose of this study.

Relative Motion Simulation Activities

Both simulations, in IVE and DVE, included the same activities with five levels of increasing complexity. In the IVE environment, the activities were presented to the participants through an nVisor SX60 (by Nvis Inc) Head Mounted Display (HMD). The HMD has a 44″ horizontal by 34″ vertical field of view (FOV) with a display resolution of 1,280 × 1,024. During the experiment, participants were placed in the center of the room (see Fig. 1) wearing the HMD. Sensors on the HMD enabled real-time simulation in which any movement of the subject's head immediately caused a corresponding change to the image rendered in the HMD. The participant's head position was tracked by 4 cameras located in each corner of the experimental room and responsive to an infrared light source mounted on the top of the HMD. The rotation of the user's head was captured by a digital compass mounted on the back of the HMD. The student was able to interact with the immersive virtual simulation (i.e., to send different commands) by using a handheld wireless remote control. For DVI condition, the students observed the simulation while looking at a conventional 2D display, and they were able to interact with the simulations using a computer mouse.

Both IVE and DVE activities were based on the same simulation module featuring two air tracks, with one glider on each track. The simulation of 1D relative motion is shown in Fig. 2a, and the simulation of 2D relative motion is shown in Fig. 2b. The module comprises virtual activities with five levels of increasing complexity. In the first three of five levels, the air tracks were aligned parallel to each other, so that students could predict and observe one-dimensional relative motion. Level 1 was an exploratory

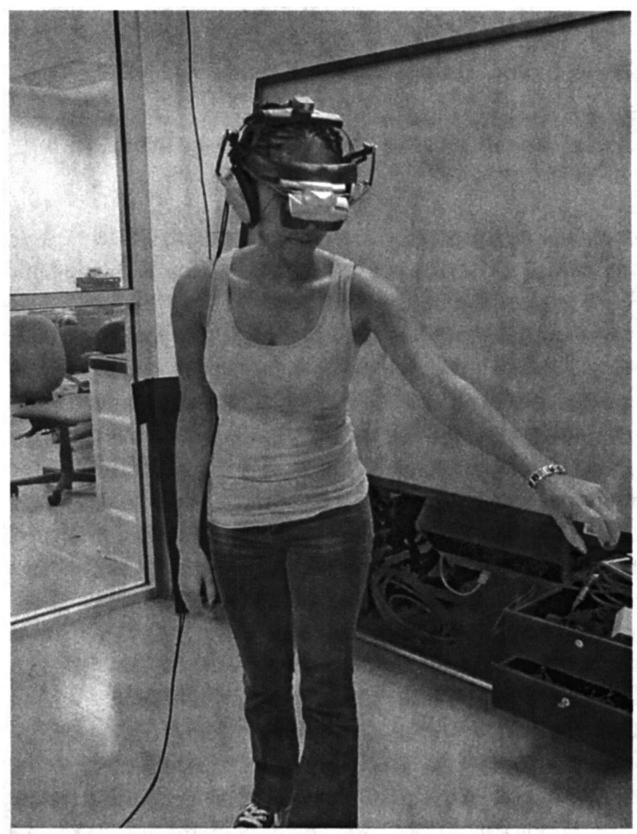

Fig. 1 Participant in IVE condition wearing HMD display

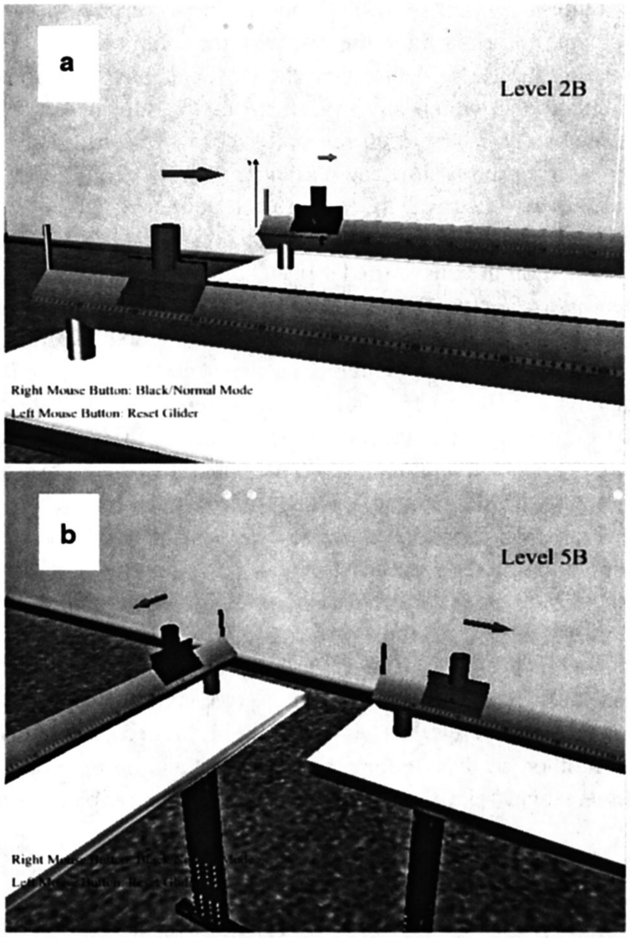

Fig. 2 A screenshot from the virtual simulations on relative motion featuring two air tracks: **a** 1D relative motion simulation, **b** 2D relative motion simulation

level, and its main purpose was to allow students to explore and adjust to virtual reality. In levels 2 and 3, students could move (virtually) with one of the gliders while observing the motion of the other glider. In levels 4 and 5, the air tracks were set up at a 90-degree angle, so that students could observe and predict two-dimensional relative motion. Except for the first level, each level included (1) an observational mode in which students observe the motion of two gliders from a laboratory frame of reference; (2) a prediction mode in which students are asked to predict the velocity (both the direction and the magnitude) of one of the gliders in the frame of reference of the other glider (in the prediction mode, students were "lifted up" to a bird's perspective in between the gliders, so that perspective distortion would not obscure their prediction of direction and magnitude, as shown in Fig. 3); and (3) a verification mode in which the students could observe the motion of one of the gliders while virtually moving on the other glider (the verification mode animation was accompanied by audio feedback on whether the prediction was correct). Students could also access an explanation mode, explaining how to compute the relative velocity.

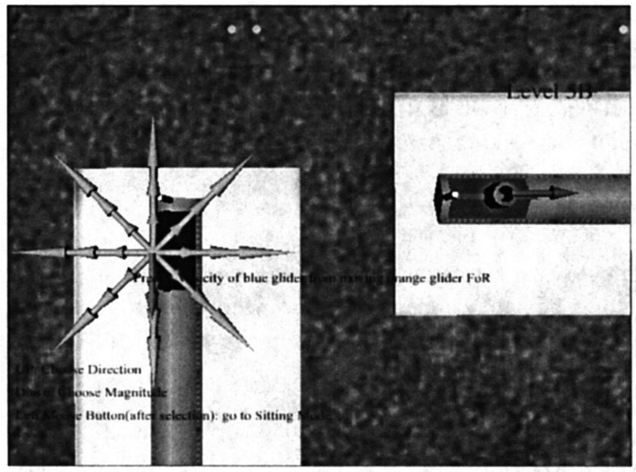

Fig. 3 A screenshot from the virtual simulation featuring the prediction mode

Students could make turns and watch the scene from different perspectives as well as switch between moving and stationary frames of reference. Arrows indicating predicted and actual relative velocities that were attached to the gliders offered feedback for the students. Students could also switch back and forth between a realistic and an impoverished "dark mode" in the virtual laboratory, in which only the two moving gliders and their relative velocity arrows were visible, to enhance the feeling that the moving glider was a new frame of reference. In addition, a grid moving with the glider (designated as the center of a new frame of reference) was shown to exaggerate the feeling that the moving glider was a new "primary" frame of reference (see Fig. 4). The subjects were videotaped performing the activities.

Results

RMPSQ

First, based on the number of formal courses taken where the relative motion topic had been taught (as was indicated in the demographic questionnaire), all the students were divided into two groups, those who received formal instruction in relative motion topics and those who had not. Then, we conducted a one-way ANOVA, with prior physics background as a predictor and their scores on RMPSQ as a criterion variable. On pre-RMPSQ ($F < 1$), students with no prior physics background and students with a prior physics background scored $M = 5.11$ ($SD = 1.83$) and $M = 4.75$ ($SD = 2.61$), respectively. On post-RMPSQ ($F < 1$), students with no prior physics

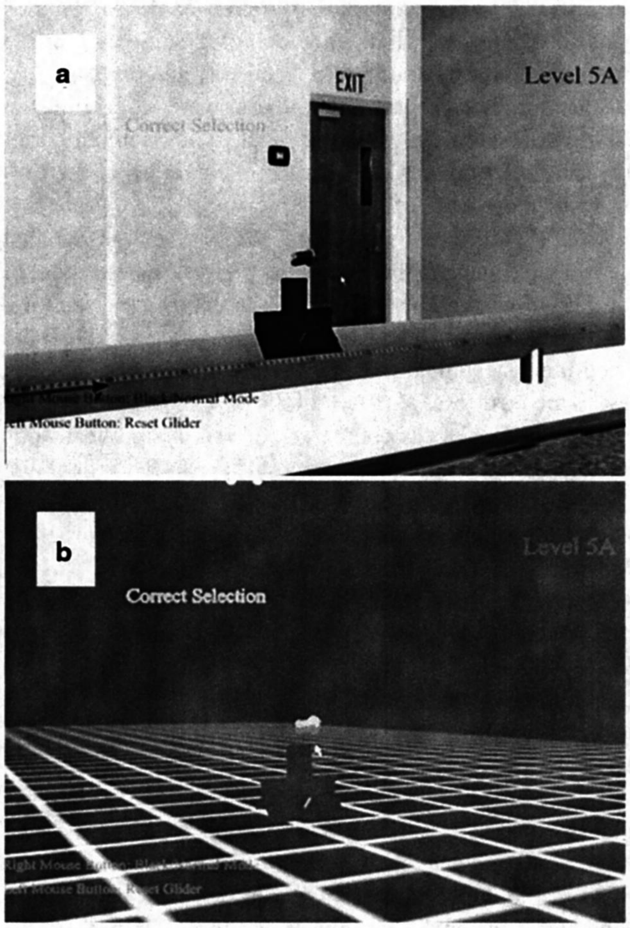

Fig. 4 **a** Realistic (virtual air-track laboratory) and **b** altered (impoverished dark mode) environments

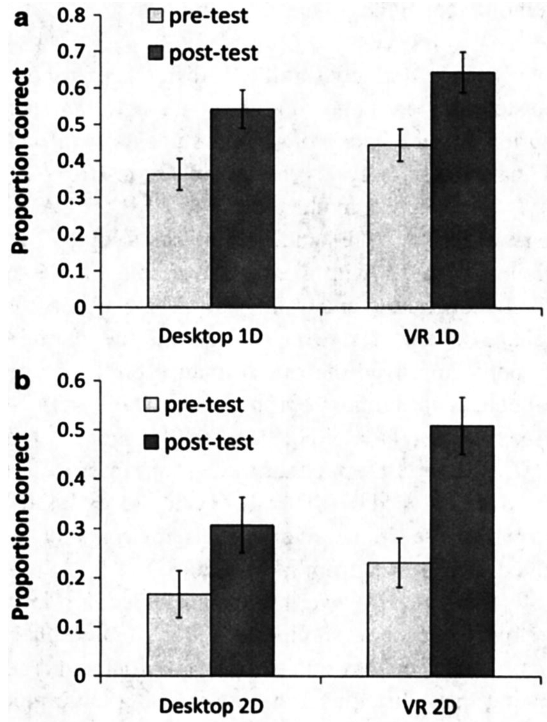

Fig. 5 Students' performance on pre- and post-RMPSQ. **a** 1D relative motion problems **b** 2D relative motion problems

background and students with a prior physics background scored $M = 8.33$ (SD = 3.67) and $M = 8.00$ (SD = 0.77), respectively. The results indicate that there was no significant difference between the two groups of students either on pre-RMSPQ or post-RMPSQ.

Second, we conducted a 2X2 MIXED ANOVA analysis with time (pre-RMPSQ and post-RMPSQ) as a within-subject variable and learning environment (DVE and IVE) as a between-subject variable. The analysis revealed that all the participants significantly improved their performance on RMPSQ from pre- to post-test: $F(1,35) = 32.27, p < 0.001$. The effect of learning environment was significant $F(1,35) = 5.40, p = 0.03$ so that overall the IVE group outperformed the DVE group. Follow-up ANOVAs indicated that the IVE group outperformed the DVE group on the post-test [$F(1,35) = 5.44$, $p < 0.05$], while both groups performed similarly on the pre-test [$F(1,35) = 1.83$, $p = 0.18$]. However, the interaction between time and learning environment was not significant, $F(1,35) = 1.20, p = 0.28$.

We found that our participants experienced more difficulties with 2D relative motion problems than with 1D relative motion problems (proportion correct on pre-test = 0.40 and 0.20 for 1D and 2D, respectively, and proportion correct on post-test = 0.59 and 0.41 for 1D and 2D, respectively). Thus, we conducted analyses for 1D and 2D relative motion problems separately. For 1D relative motion problems, repeated measures ANOVA with time as within-subject variable and learning environment as between-subject variable revealed an overall significant improvement from pre-test to post-test [$F(1,35) = 24.30$, $p < 0.001$]. However, neither the effect of learning environment [$F(1,35) = 2.52, p = 0.12$] nor the interaction between time and learning environment ($F < 1$) were significant (see Fig. 5a). This suggests that for 1D problems, both groups performed similarly on both pre-RMPSQ and post-RMPSQ.

For 2D relative motion problems, although the analysis revealed an overall significant improvement from pre-test to post-test for all the participants [$F(1,35) = 23.58$, $p < 0.001$], there was a significant effect of learning environment [$F(1,35) = 6.63$, $p = 0.01$] and marginally significant interaction between time and environment [$F(1,35) = 3.47$, $p = 0.07$] (see Fig. 5b). In fact, follow-up ANOVAs indicated that while there was no significant difference between these two groups on pre-test ($F < 1$), the difference between them on the post-test was significant [$F(1,36) = 10.09$, $p = 0.003$], so that students in immersive conditions outperformed those in desktop conditions on the post-test.

Epistemological Beliefs Questionnaire

First, we did not find any significant difference in scores on the epistemological belief questionnaire between students with prior physics background and students who had not taken introductory physics, either on pre-test or post-test ($Fs < 1$). Second, we conducted a 2 × 2 MIXED ANOVA analysis with time (pre- and post-epistemological beliefs questionnaire) as a within-subject variable and learning environment (desktop and immersive) as a between-subject variable. The analysis revealed that all the participants significantly improved their performance on the epistemological beliefs questionnaire from pre-test ($M = 4.14$(SD = 0.80)) to post-test ($M = 4.50$(SD = 0.89)): $F(1,35) = 5.25$, $p = 0.03$. The desktop condition group improved their scores from $M = 4.07$(SD = 0.73) to $M = 4.43$(SD = 0.86), while the immersive virtual environment group improved their scores from $M = 4.20$(SD = 0.88) to $M = 4.56$(SD = 0.92). However, the main effect of learning environment was not significant ($F < 1$), in either the interaction between time and learning environment ($F < 1$), suggesting that participants in both learning environments improved similarly from pre- to post-test.

An Open-Ended Questionnaire

Students' responses on an open-ended questionnaire were categorized into four categories denoted four hierarchical stages of conceptual development (see Table 1 for examples). We suggest that the proposed categories reflect the development of students' conceptual models of relative motion, starting from the lack of any ideas what relative motion means (Category 1) to a naïve idea about relative motion as just an "illusion" (Category 2), then progressing to an egocentric idea about relative motion that it is always encoded in relation to an individual's own perspective (Category 3), and finally shifting toward a scientific view that the relative motion could be encoded relative to any object moving or being stationary in the original laboratory frame of reference (Category 4).

The analysis revealed that there were no significant differences between students with and without prior physics background with regard to their stages of conceptual development of relative motion: [χ^2 (3) = 5.6, $p = 0.13$]. Most of the subjects (63 %) were in the first category (no understanding) on the pre-test, independent of their prior physics background (Fig. 6). As we can see from Fig. 6, there was a clear tendency to shift toward a more scientific conceptual model of relative motion from the pre-test to the post-test [χ^2 (9) = 14.85, $p = 0.047$, one-tailed].

We also analyzed whether there was a significant difference between the conceptual shift in IVE versus DVE groups. (The shift was encoded as "0," "1," "2," or "3" if a student progressed none, one, two, or three categories up between pre- and post-test, respectively.) There was no difference in the degree of the conceptual shift between IVE versus DVE groups [χ^2 (3) = 4.7, $p = 0.2$].

Concluding Questionnaire

The individual responses about which aspects of the simulation they found particularly helpful in understanding the concept of relative motion and which aspects they did not find useful were grouped together and are summarized in Table 2.

As Table 2 shows, the simulation was rated by all students as a valuable visualization tool. The use of the impoverished "dark mode" of the virtual laboratory was reported as a helpful tool for understanding that motion is relative. The possibility of switching back and forth between different frames of reference helped students realize that motion looks different in different frames of reference. It is interesting that there were more students in the IVE group emphasizing the advantages of "dark mode" and the ability to shift between different frames of

Table 1 Stages in conceptual development of relative motion

	Description	Example of students' responses
Category 1	No basic understanding of relative motion concept	S2: The motion of an object affected by outside forces (i.e., gravity) S21: It is the motion that occurs indirectly or because of something else
Category 2	Relative motion is not a real motion but a visual perception (Stationary object remains stationary, only perceived to move or "look like" moving)	S6: Items that are stationary but appear to be moving because I am moving S8: Relative motion is the perception of motion of an object from another frame of reference than that object (even if the object in question is not moving)
Category 3	Relative motion is always encoded relative to the person's own perspective (egocentric approach)	S13: Relative motion is what is relative to where you are S30: Relative motion is how fast/slow something moves in relevance to you
Category 4	Generalized understanding (fluent to apply relative to any object)	S1: a physics term to describe how objects move relative to each other S10: Motion relative to the perspective that it is viewed from S12: The movement of something in relation to another item/person/place

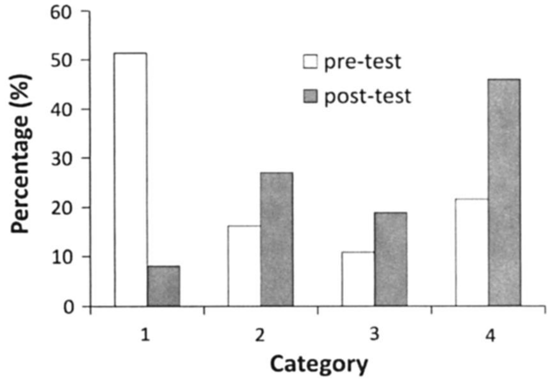

Fig. 6 Stages (categories) of conceptual development of relative motion

reference than in the DVE group, suggesting that these two features are more helpful in immersive virtual reality due to its egocentric visualization.

Most of the students did not report any major technical or other problems or difficulties with the module. (In fact, 60 % of the DVE group and 45 % of the IVE group reported that they had not experienced any problems at all.) The only notable concern was one reported by several IVE students that the immersive VR equipment was not very comfortable (e.g., HMD weight, more difficulty in control, etc.).

Discussion

The main goal of this research was to evaluate the potential of virtual simulations in learning relative motion concepts. The findings of this study suggest that carefully designed virtual simulations in either non-immersive or immersive virtual environments improve students' understanding of relative motion concepts. Indeed, students who participated in the simulation activities (both IVE and DVE) exhibited a significant improvement on relative motion problem-solving tests as well as a significant shift toward a scientific understanding in their conceptual understanding and epistemological beliefs about the nature of relative motion. Interestingly, there was no significant difference on any of the pre-test measures from the relative motion assessment battery between students with prior physics background and those who had not taken any formal courses in physics, indicating that traditional physics instruction is not effective in eliminating students' naïve beliefs about relative motion. Indeed, as previous research shows, these naive misconceptions are resistant to change as a result of traditional instruction and require specific visualization tools to foster the generation of appropriate visual models (Monaghan and Clement 1999, 2000).

As was evident from students' reports in a concluding questionnaire, different visualization tools that allowed switching back and forth between different frames of reference and "turning off and on" the laboratory frame of reference ("dark" mode) provided students with new experiences leading to a formation of more advanced conceptual models about relative motion. In particular, as students reported in the concluding questionnaire, "dark" mode allowed them to dissociate themselves from a stationary laboratory frame of reference and observe from a

Table 2 Students' reports on helpful aspects of the simulation

Helpful aspects	Example of responses	Frequency of citations	
		IVE condition (%)	DVE condition (%)
General visualization of the environment	S4: "It is a good way to do things you can't otherwise do. It was interesting to 'move' magically around the environment" S6: "For whatever reason, I had a much easier time determining relative motion in VR than via pictures on paper"	55	50
Impoverished "dark mode" of the virtual laboratory	S1: "When I put it into the coordinate mode, it is more apparent because all of the distractions [were gone], elements were visible by themselves" S18: "It made the concept a bit easier to grasp, since you can focus your attention solely on the moving object [from] any frame of reference" S19: "Greatly increased my understanding. I could clearly see how the object was moving relative to my movement"	36	21
Switching between frames of reference	S2: "Being able to flip back and forth between the black and the actual really helps visualize what is going on" S19: "'Sitting' on the moving object and seeing the other object's movement" S33: "It showed what I had to imagine in my head. By looking at it, not imagining, it was easier to learn what relative motion is"	27	7

first-hand perspective the motion of other objects from a moving frame of reference (when they were riding on a moving glider). It should be noted that this experience is more salient in IVE than in DVE conditions. Indeed, recent research in the field of human–computer interaction (Kozhenikov and Dhond 2012) indicates that an IVE environment encourages the use of viewer-centered encoding, where the presented scene is encoded egocentrically, that is, in relation to the body and the gaze direction of the observer. In contrast, the scene presented on a 2D computer screen is encoded allocentrically, that is, in relation to the standard orthogonal directions or a salient object in the environment such as the sides of a computer screen. These differences in object encoding lead to different perceptions of the objects in a scene. Since the IVE observers feel like they constitute a part of an environment in which they are immersed, they perceive their experiences with objects in IVEs as more realistic (especially if they involve a mental transformation of the observer's body as in the case of visualizing oneself riding on a moving glider) than similar experiences in non-immersive environments where the observer is just observing the scene from the "outside."

Indeed, educational research also reports that "first-hand," egocentric experiences in a virtual environment can significantly contribute to the sense of "presence" students feel in a virtual environment (Barfield and Hendrix 1995; Clancey 1993; Hoffman et al. 1995; Zeltzer 1992; Winn et al. 1997). The "first-person" egocentric experience could explain why we found the advantage of IVE versus DVE on the RMPSQ, specifically on solving two-dimensional relative motion problems. Two-dimensional relative motion problems were more difficult than one-dimensional motion problems, possibly because most of the one-dimensional problems were presented in a context familiar to students (e.g., two cars moving toward each other) and thus were relatively easy for students. Two-dimensional problems, in contrast, required more visualization strategies. While both virtual environments provided an appropriate context not often encountered in everyday life about two-dimensional relative motion, it appears that the experience was more convincing and realistic in IVE than in DVE, possibly due to the egocentric viewer-centered encoding of the scene in IVE.

The findings of the present study have implications for the designers and evaluators of immersive virtual reality systems. Currently, we have little information concerning which of virtual reality's features provide the most support for enhancing complex conceptual learning. The results of this study suggest that aspects of virtual realities such as immersivity, first-hand experience, and the ability to change different frame of references can facilitate understanding abstract science phenomena and help in displacing intuitive misconceptions with more accurate mental models. Future research should also incorporate more realistic 3D immersive environments (e.g., a virtual city with moving cars and walking avatars) in addition to the laboratory setting (with air tracks and gliders) reported in this study. It will provide an additional bridging between "real-life" and laboratory virtual environments, and we expect it to be highly beneficial in constructing valid conceptual models of real-world situations.

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Appendix 1: Epistemological Belief Questionnaire

Make a cross on the vertical lines that represent your opinions

1. Objects, which are moving in the real world, have one true velocity.

Strongly disagree Strongly agree

2. There is one true velocity.

Strongly disagree Strongly agree

3. The movement of the same object can be different from different perspectives.

Strongly disagree Strongly agree

4. Some objects (e.g., houses, trees, etc.) cannot move relative to you.

Strongly disagree Strongly agree

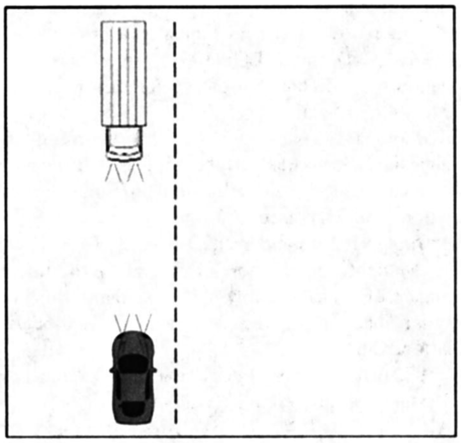
5. An object can be seen moving and not moving from different views.

Strongly disagree Strongly agree

Appendix 2: Relative Motion Problem Solving Questionnaire (*an extract of two problems*)

Please try to answer the following questionnaires. If you are not able to answer a question, please write "don't know."

1. In the figure below, you are in the gray car. Your speedometer reads 40 km/h.



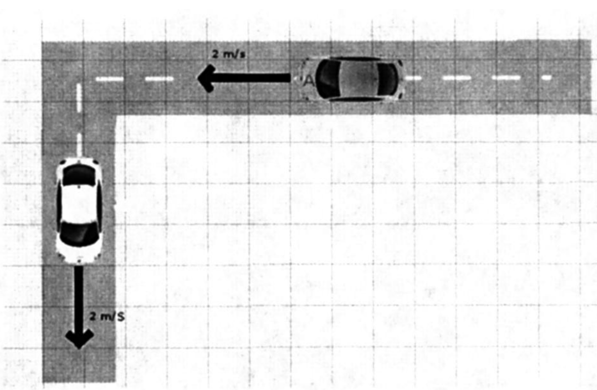
(a) **What is your car's speed, relative to a very low flying helicopter going exactly in the same direction as your car, at a speed of 200 km/h relative to the ground?**

Answer: ________________km/h.

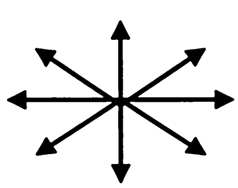
(b) **A white truck is traveling toward you. If the truck's speedometer reads 40 km/h, what is the truck's speed relative to the helicopter?**

Answer:________________km/h.

2. Two cars are driving along a rectangular road, as shown in the figure below. They are both driving with the same speed.



Circle the tip of the arrow that represents the velocity of the white car from gray car's frame of reference.



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