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The impact of an online inquiry-based learning environment addressing misconceptions on students' performance

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Abstract

This study sought to develop and evaluate an online module based on inquiry learning with digital laboratories, which was intended to address students' misconceptions in a science domain. In a quasi-experimental design, 171 first-year students in a higher education introductory physics course on circular motion were as their existing groups assigned to an experimental ($n = 100$) or a control ($n = 71$) condition. The experimental condition was developed by arranging online inquiry activities that would encourage students to probe five identified misconceptions. The control condition required students to engage in online inquiry following the traditional syllabus outline. Students in both conditions used the same type of digital laboratory setup. The participants learned about the topic of circular motion and their knowledge was assessed. Results of the knowledge test revealed that the experimental condition geared towards addressing students' misconceptions facilitated conceptual change more than the control condition.

Keywords: Circular motion, Inquiry-based learning, Misconceptions, Digital laboratories

Background

In physics education research, an increasing effort is being made to establish effective pedagogical strategies that follow learner-centered teaching methods, which may, in turn, facilitate changing students' alternative conceptions into correct conceptual understandings (Al Mamun et al., 2020; Chinn & Duncan, 2021; Dahn et al., 2021; de Jong, 2022; Fukuda et al., 2022; Gerard & Linn, 2022; Joshi & Lau, in press; Schulze et al., 2000; Spronken-Smith, 2012; Wu et al., 2021). Correct conceptual understanding refers to having well-defined structural relations between concepts that are in line with what the theory proposes (de Jong et al., 1996). Already early, Bruner (1960) asserted that learners develop the initial meaning of concepts primarily from the experiences they have with nature; this means that often learners have constructed an alternative concept to explain the encountered phenomena before they hear about the correct scientific conceptual understanding (Eaton et al., 2019). Later on, students also tend to keep their convenient alternative explanations of phenomena they experience without considering the

existing scientific explanations for the given subject (Adair, 2013; Gunstone, 1984; Halloun & Hestenes, 1985). The concept of circular motion (CM) is a phenomenon experienced by everyone daily, thereby creating room for alternative conceptions on the topic before learners are taught the correct conceptual understanding (Canlas, 2016). The current study sought to investigate ways to use a learner-centered approach in the form of an online inquiry-based learning (IBL) environment for teaching CM to first-year undergraduate students in an introductory physics course.

To effectively engage the students in changing their alternative conceptions, it is important to use a learning approach that compels them to actively reconsider their existing conceptions and to construct new conceptions (Ching, 1999; Furtak et al., 2012; Halloun & Hestenes, 1985). IBL is an approach used in higher education that can engage students in such an active learning process (Canlas, 2016; Ching, 1999; Spronken-Smith, 2012). Spronken-Smith (2012) described IBL as a process in which students are actively engaged in knowledge creation that pushes them towards self-directed learning. In IBL, students are compelled to be responsible for their learning by challenging their initial ideas against self-generated data and by actively restructuring their knowledge base (Abd-El-Khalick et al., 2004; de Jong, 2006). In IBL, students often follow an inquiry cycle, bringing them from conceptualization, through experiment design and investigations, to data analysis and reconceptualization (de Jong, 2022; Pedaste et al., 2015). In this way, IBL is also seen as a way to confront students with their naïve conceptions and stimulate them to exchange such conceptions for theoretically sound notions (Kapici et al., 2019; Brod et al., 2018; Maskiewicz & Lineback, 2013; Posner et al., 1982). IBL is traditionally done with real materials and equipment, but nowadays simulations or digital labs are seen as an effective alternative (de Jong, 2022; de Jong et al., 2013).

Overall, the results of using inquiry learning for reaching conceptual understanding have been favorable (Furtak et al., 2012), and the use of digital laboratories and labs for inquiry learning is even more promising (see e.g., Lazonder & Harmsen, 2016; Smetana & Bell, 2012). However, still greater results could potentially be reached when a digital lab is used and the instructional context is designed in such a way that cognitive conflict and conceptual change are elicited. Baser (2006), for example, used two instructional designs for the same simulation about electrical circuits. In one design, students mainly confirmed knowledge they had gathered before; in the other design students were systematically guided towards experiencing and resolving a cognitive conflict. Results showed a clear advantage in conceptual knowledge gained for the cognitive conflict condition. Dega et al. (2013), also working in the domain of electricity, used two approaches around computer simulations for confronting students with their naïve conceptions. One approach led students to move more gradually away from their naïve conceptions, while the other used a more radical approach. They found an advantage for the more gradual approach on conceptual knowledge. Zohar and Aharon-Kravetsky (2005) found that a cognitive conflict approach worked for students with high academic achievement, but was less favorable for students with lower academic achievement levels. In an extensive overview, Limón (2001) gave a number of reasons why inducing cognitive conflict may not result in conceptual change, which includes the lack of motivation to change and of adequate learning strategies. In the current study, we have focused on known

naïve conceptions in the field of CM in order to induce cognitive conflict in students. By presenting known naïve conceptions, we intended to rouse students' motivation for change. Additionally, for each of the identified misconceptions we had students create a hypothesis. This approach was based on the work by (Brod et al., 2018) who found that when students were confronted with experiment outcomes that violated their expectations they exhibited surprise responses (as measured by pupillary responses) and that the strength of this reaction was associated with better learning.

In CM, alternative, naïve, conceptions are usually based on Aristotelian ideas regarding first-hand experiences of everyday interactions with natural phenomena (Jimoyianis & Komis, 2001). Ching (1999) outlined five prominent alternative conceptions about CM: (1) assuming that objects will continue on curvilinear paths in the absence of centripetal force, which arises from medieval impetus theory; (2) mixing of representations, with diagrams from a horizontal plane taken as vertically placed; (3) thinking that the centripetal force is different from the resultant force; (4) assuming that there must be a motive force that causes motion in the direction of the force, arising from Aristotelian ideas; (5) thinking that there must be an outward force acting on a body for it to move in CM. Canlas (2016) identified several related concepts for which learners have alternative conceptions, such as linear speed, rotational speed, velocity, acceleration and centripetal force. Those misconceptions have also been attributed by some scholars to the implied force theory known as impetus theory (Gunstone, 1984; Searle, 1985). Canlas further recommended the use of inquiry-based learning as a good teaching tool for changing alternative conceptions to a scientific conceptual understanding of the topic of CM (Canlas, 2015). This recommendation was based on this teaching approach being learner-centered and allowing students to engage in the process of scientific research as scientists do (Canlas, 2016).

The current study was conducted within the context of the Go-Lab ecosystem (de Jong et al., 2021). Go-Lab is a digital ecosystem for creating and running Inquiry Learning Spaces (ILSs). In an ILS, students proceed through a set of inquiry phases to work through an inquiry cycle, as in the model presented by (Pedaste et al., 2015). The phases in an ILS are populated with an online lab (or labs), multimedia material, and applications (apps). These apps are small digital tools that guide the students in performing specific inquiry processes such as creating hypotheses or setting up an experiment (de Jong, 2019; Pedaste et al., 2015). This type of scaffolding plays an important role in achieving positive effects of inquiry learning (Lazonder & Harmsen, 2016). In the current study, our main goal was to investigate the relative effectiveness of two ILSs designed around the topic of CM, more specifically, around the use of Newtonian laws to resolve the movement of bodies in circular paths. One ILS followed a traditional approach and focused on presenting and investigating the correct conceptions about the topic, whereas the second ILS was geared towards addressing students' specific misconceptions.

In summary, the current study sought to answer as its main question: How does an ILS geared towards addressing misconceptions compare to an ILS that follows the traditional inquiry approach with regard to development of students' conceptual knowledge about circular motion?

Methods

Participants

First-year students enrolled in a foundational introductory course in physics at a public university participated in the study. CM is one of the topics taught in the introductory physics course. Students who complete the course requirements for the foundational science and mathematics courses can then apply to pursue science-related programs in other schools (engineering, medicine, and mining) as well as within this school in its various departments.

A quasi-experimental design was used to compare the performance of students in the control group (traditional ILS set-up) with that of the students in the experimental group (ILS geared towards remedying misconceptions). The sample comprised 171 students, who attended their existing laboratory sessions in two separate groups. A toss of a coin was used to determine which of the groups was assigned to the traditional ILS (control group; $n=71$) and to the misconception-geared ILS (experimental group; $n=100$). Ethical guidelines from the research council of the university when dealing with human subjects were followed when conducting the study.

Instrumentation

To measure students' knowledge of Circular Motion we used a test that we labelled CMAT. The CMAT was adopted from Ching (1999) and was developed to measure students' conceptual understanding of CM. The test had four main items, each intended to address one of the CM misconceptions identified by Ching. Although Ching identified five misconceptions, two of the misconceptions are based on the same concept and, therefore, a total of four items was adequate to assess the students' conceptual understanding. All main items had the same format and consisted of one or more short-answer questions and follow-up questions requiring the respondent to give a brief explanation of their answer. This instrument was developed in two equivalent forms, to be used as pre- and post-test in the study. The Pearson product-moment correlation coefficient between the scores on the pre- and post-test was found to be 0.7. The pre- and post-test versions are included in the Appendix (Additional files 1, 2). In the first item, students were required to consider the resultant path of objects in CM. In the pre-test, the object was a small metal ball, while for the post-test they were cars of different masses. This item assessed the first misconception about objects continuing in curvilinear paths in the absence of centripetal force. Item 2 assessed the direction of the centripetal force, probing the third and fifth misconceptions. The pre-test involved a stone tied to a string moving in CM, while the post-test used the orbital movement of the earth around the sun.¹ The third item in both tests assessed the influence of the radius length on the circular path, hence probing the fourth misconception. The fourth item required students to determine the components of the force that acts on an object in CM and is related to the second misconception. In the pre-test, the students labelled the forces that act on the earth and moon as the latter moves in a circular motion, while the post-test included a

¹ The orbital movement of the solar system was assumed to be circular for the students to enable them to perform calculations.

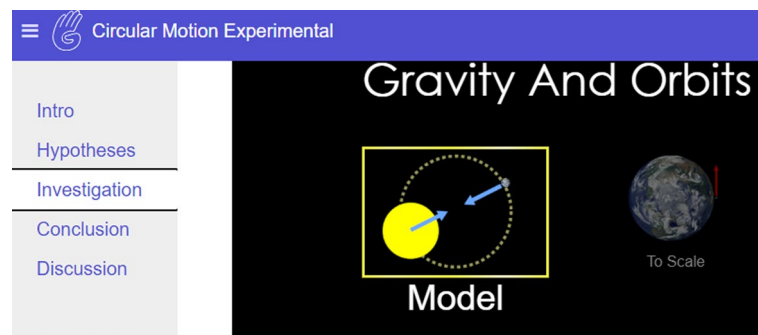


Fig. 1 Phases of an ILS showing the investigation phase with a PhET simulation (This simulation lab was designed by PhET Interactive Simulations, University of Colorado Boulder, licensed under CC-BY 4.0. <https://phet.colorado.edu>.)

bob on a string attached to a fixed point. Students identified the forces that were acting on the bob and the moon and described the resultant forces.

An initial version of the CMAT was submitted to four physics teachers who had at least six years of teaching experience, to check the instrument's validity. These teachers confirmed that the instrument (CMAT) was within the content requirements for the topic of circular motion and within the capabilities of the first-year students. The reliability of the CMAT for the post-test was 0.81 (Cronbach's α).

Inquiry learning spaces

The ILS for the experimental condition was tailored towards addressing the identified possible misconceptions, while the one for the control condition provided inquiry activities focusing on the outlined curriculum requirement for CM, which does not take into consideration the misconceptions that students may have.

Both ILSs followed the same general design, in which the model presented by Authors. Of the basic inquiry phases was used to shape the overall structure of both ILSs (Pedaste et al., 2015). As a consequence, the overall design of both ILSs followed five phases, namely: introduction, hypotheses, investigation, conclusion, and discussion. Figure 1 shows the phases of the ILSs, on the left-hand side, in the student view. In this figure, the student is in the Investigation phase.

The introduction was meant to create an appealing context that would cause the students to appreciate the importance of the topic they were learning about as related to a real-life theme. When introducing the topic of CM, students' attention was drawn to objects in their everyday life that experience this type of motion, such as the motion of cars around curves and the motion of the earth around the sun. In both conditions, students discussed their observations. The hypotheses phase presented detailed conceptual information on the topic and required the students to generate hypotheses on the relationships between various CM-related concepts using a hypothesis scratchpad (see Fig. 2). In the investigation phase, students were provided with online laboratories with which they could perform experiments to test their hypotheses. Students then wrote up

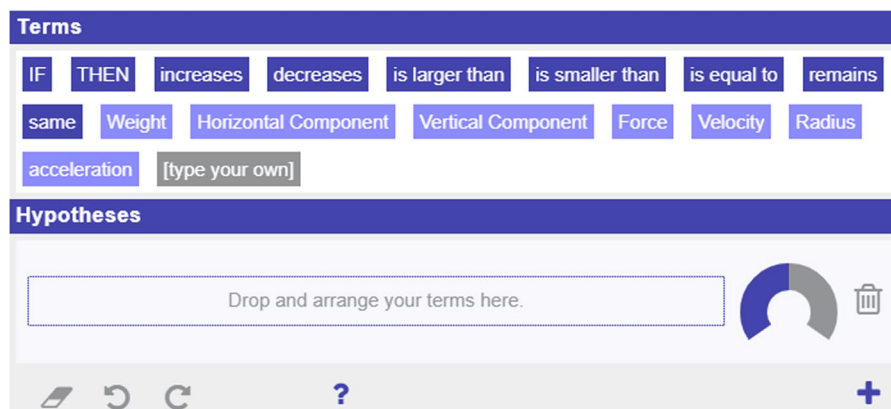


Fig. 2 The hypothesis scratchpad as used in the control condition

their findings in the conclusion phase and sought relationships between the concepts they had investigated. In the discussion phase, the students were required to discuss with their classmates with the use of an online discussion tool and suggest any improvements they would make to their investigations and findings.

Control condition ILS

In the introduction phase of this ILS, which was the same as in the experimental ILS, the students were asked to observe images of objects experiencing CM, discuss them and write down what was common across the images. The hypotheses phase in the control ILS was designed following only the requirements from the course outline. The relations that were emphasized were:

1. To derive the relation between linear velocity and angular velocity.
2. To show that centripetal acceleration is given by $a = r\omega^2$ and that $a = V^2/r$.

The students created their hypotheses about these two relations using the hypothesis scratchpad as shown in Fig. 2.

In the investigation phase, a velocity-radius simulation² was used to observe the relations between velocity, acceleration, and the radius of the path of the ball experiencing uniform CM. Students had to use sliders in the simulation to adjust the speed and the radius of the path, and in this way could test their hypotheses.

In the conclusion phase, the students were required to describe their findings concerning the hypotheses they had generated. If what they wrote in the hypotheses was at variance with the investigation, they were asked to adjust their hypotheses and run the simulation again.

In the discussion phase, the students were provided with an online discussion tool in which they shared their observations and considerations with other students.

² This simulation lab was designed by Physlets, Davidson College, licensed under CC-BY 4.0. <http://physics.bu.edu/~duffy/classroom.html>.

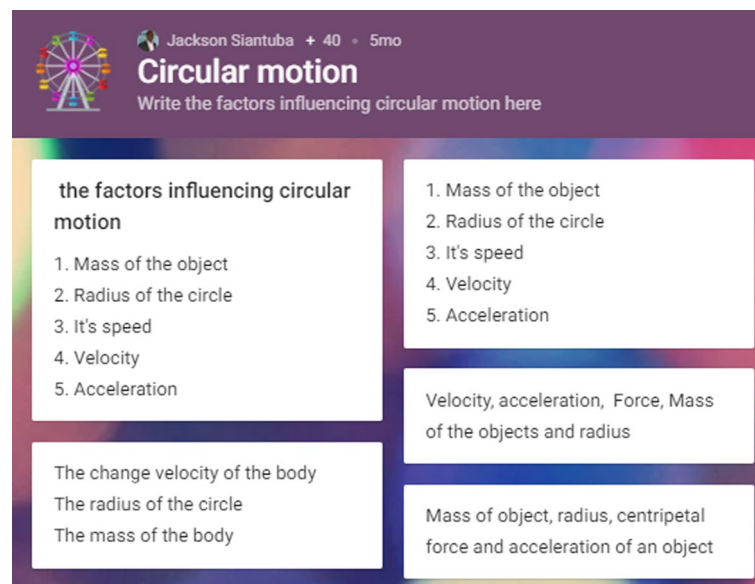


Fig. 3 Padlet postings by students

Experimental condition ILS

The ILS for the experimental condition was designed to address potential misconceptions. The introduction phase was the same as for the control condition. The hypothesis phase included a Padlet, an input box, and a hypothesis scratchpad. The Padlet is a form of (electronic) notice board. Figure 3 shows some of students' postings on the Padlet. The Padlet was used as an interactive forum for students to share their views on factors that would influence an object that is moving in CM, and in this way to make their misconceptions apparent. The Padlet was used to further expose the apparent potential misconceptions that students had. The hypothesis tool was used to let students formulate their hypotheses about the relationships between mass, velocity, acceleration, and force for an object that is moving in CM. The presentation in the hypothesis phase was arranged to follow the five areas of misconception from (Ching, 1999). Students were required to form a hypothesis for each area of misconception. They had to write in the Padlet factors that influenced the motion of objects experiencing CM.

Two online laboratories were included in the investigation phase: "the uniform circular motion simulation", and the "gravity and orbits simulation".³ The uniform circular motion simulation (see Fig. 4) was used to address three misconceptions, namely: the first misconception assuming that objects would continue on curvilinear paths in the absence of centripetal force, the third misconception that the centripetal force is different from the resultant force, and the fifth misconception that there should be an outward force acting on a body to keep it moving in CM. The simulation was used to demonstrate how the vector components of velocity, acceleration and force are represented for an object experiencing CM. Students inferred the presence of velocity as

³ The "uniform circular motion" simulation was developed by Walter-Fendt; the "gravity and orbits" simulation was developed by the PhET team, see Footnote 2.

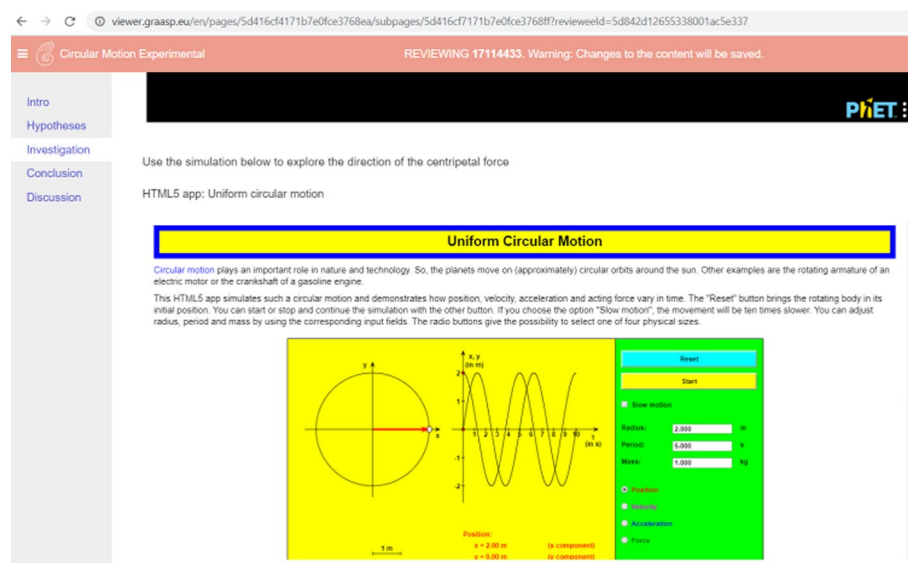


Fig. 4 Display for the uniform circular motion simulation

being produced by a centripetal force whose direction was shown in the simulation. They varied the magnitude of force and recorded the resulting velocity. Students also observed the changes in the coordinates for the x-axis and y-axis at any point in the circular path. To address the first misconception, they clicked on the force icon and observed the resultant force vector with its direction at several instances throughout the circular path; when no force is present, they observed whether the object would continue in curvilinear motion. For the third misconception, students explored the direction of the force that causes an object to move in CM by varying the radius of the circular path and observing the x-component and y-component of forces and the resultant, which is the centripetal force.

The gravity and orbits simulation shows how planetary bodies' motion is influenced by mass, velocity and the radius of their orbit. This application was used to further address the third misconception that the centripetal force is different from the resultant force, and the fourth misconception about assuming that there must be a motive force that causes motion in the direction of the force. The students varied the radius between the sun and a planet and observed whether the planet continued on a circular path. They observed the direction of the gravitational forces and noted the resultant force acting on the planet that was moving in CM. Students used the planets and orbits simulation to investigate the effect of changing the centripetal force acting on a planet. They were required to tabulate the result for a range of forces and formulate a conclusion for the direction of motion of an object in the absence of a centripetal force.

At the time of the study, no simulation was available for addressing the second misconception. Therefore, for the vertical and horizontal representations of the circular path of an object, students were provided with physical strings and bobs. They caused the bobs to swing in CM, first in the horizontal plane and then in the vertical plane. After observing the tension in the string at four points (four opposite sides of

the circular path in the horizontal plane and up, down and sideways for the vertical plane), the students were required to draw free body diagrams and state the forces acting on the bob and the resultant force.

In the conclusion phase, students were presented with an image of an athlete swinging a ball in a circular path in a horizontal plane. They were required to describe the path of motion of the ball when the string breaks. Their responses were supposed to be related to the findings in their investigation phase. An observation app was provided for the students to state their observations and relate their observations to the hypotheses they generated.

Finally, in the discussion phase, students were required to consolidate what they learned by using a quiz tool. The correct answers to the quiz questions were provided after students had answered. Then students were required to watch an animation of a summary of the principles that govern the CM experienced by an object.

Procedure

The pre-test was administered (paper-based) before the students were taught. The two groups were then taught for 4 lecture hours each. Students used their devices during the learning sessions and on their own time, and were allowed to discuss with each other as they worked through each phase. The instructor explained the concepts in each phase and required students to participate by using the provided input apps in the ILS. At the end of the four lecture sessions, the students took the paper-based post-test.

Results

Common misconceptions

The results from the CMAT pre-test for both conditions (experimental and control) revealed eight prominent misconceptions that students exhibited. These misconceptions can be summarized within the five categories from (Ching, 1999) that we used as a basis for this study. The following is a list of the misconceptions that were prevalent among the students.

1. Students perceived that objects would continue moving in CM in the absence of a centripetal force. They regarded an object moving in CM as observing Newton's first law of motion.
2. Students regarded planetary objects in orbit around the sun to be experiencing a gravitational force oriented vertically downwards. They wrote free body diagrams that included a component representing weight, pointing in the conventional downwards direction.
3. Students regarded centripetal force as balanced by a centrifugal force.
4. Students perceived that there must be a motive force in the direction of motion for a body that is moving in CM.
5. Students regarded centripetal force as different from the resultant force for an object moving in CM.
6. Students interchanged concepts between velocity, acceleration, and force.
7. Students perceived the net force acting on the moon as zero and viewed motion in a circle to be a stable state of an object.
8. Students thought that an object's ability to follow a circular path depends on its mass.

Table 1 Descriptive statistics for the pre-test and post-test (% correct)

| GROUP | n | Pre-test (max = 85) | | Post-test (max = 90) | |
|--------------|-----|---------------------|-------|----------------------|-------|
| | | Mean (%) | SD | Mean (%) | SD |
| Control | 71 | 35.71 | 20.87 | 36.73 | 22.85 |
| Experimental | 100 | 37.86 | 20.89 | 50.81 | 19.81 |
| Total | 171 | 36.96 | 20.85 | 44.97 | 22.18 |

Misconceptions 1, 7 and 8 on this list relate to Ching's first misconception. Misconception 2 on this list relates to the Ching's second misconception. Misconceptions 4 and 5 on the list relate to Ching's fourth misconception. Misconception 3 on the list relates to Ching's fifth misconception. Finally, the 6th misconception about concept mapping relates to all of Ching's misconception categories.

The presence of these misconceptions was confirmed by observations of students' discussions while in the introduction phase of the ILSs (this phase was the same for both ILSs and preceded the actual knowledge acquisition phases). The following are some extracts of their responses about what they observed as being common in the images that were presented to them, written during the introduction phase of the ILS:

They all possess circular motion.

They are all moving in a circular motion about an axis of rotation.

When asked to explain what makes it possible for drivers to drive on a vertically curved track, students responded in the following ways:

The friction force between the wall and the tires provides the centripetal force. And the speed, caused by tangential acceleration increases at a very high rate hence making it possible to overcome gravity and travel in a circular manner.

It can be said that as an object moves along a circular path, it develops enough force allowing it to revolve around. In the case of the car, it seemingly defies gravity due to the high-speed motion being produced by the engine. This force allows it to continue moving in that path (overcoming gravity). Note that gravity is still acting on the car but it's producing enough horizontal force to oppose it. It would continue moving in that path regardless of friction if the force is left supplied.

Notably, the students identified CM as a natural state of motion instead of being caused by the action of a centripetal force. The introduction also sparked the students' engagement with their beliefs about CM.

Conceptual understanding

Table 1 shows the descriptive statistics for the scores on the pre-test and post-test and their standard deviations.

To test whether there was any difference in prior knowledge between the two conditions, an ANOVA was conducted, which found that the difference between the pre-test

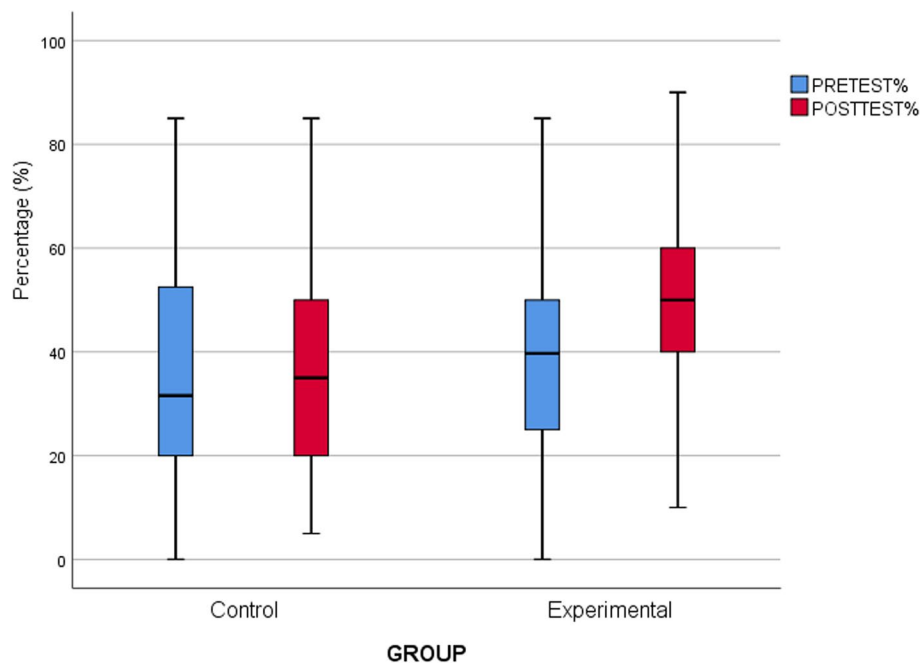


Fig. 5 Box and whiskers plot of pre-test and post-test scores

mean score for the experimental group (35.71%) and the control group (37.86%) was not statistically significant, $F(1)=0.439$, $p=0.509$. The students, therefore, had a similar understanding of the CM topic before the intervention was implemented. Figure 5 shows the distribution of scores in the experimental and control groups. There were no outlier scores in the distribution. The range of scores in the control group for the pre-test was from 0 to 85%, while it was from 5 to 85% for the post-test. The range of scores for the experimental group in the pre-test was from 0 to 85% while in the post-test it was from 15 to 90%.

A one-way ANCOVA was conducted to compare the effectiveness of the ILS geared towards addressing students' misconception about circular motion with that of the ILS following the curricular objectives, while controlling for the students' prior knowledge (pre-test score). Levene's test and normality checks were carried out, showing that all assumptions were met. The ANCOVA for the post-test scores of the experimental versus control groups while controlling for the pre-test scores was found to be statistically significant, $F(1.168)=21.520$, $p=0.000$, $d=0.114$. This result indicates that the difference in knowledge gain between students who were taught using the ILS geared towards addressing misconceptions about circular motion and the students who were taught using the ILS in the control condition was statistically significant.

Conclusion

Active or engaged forms of learning, such as inquiry learning, are gaining ground in STEM education because they lead to improved learning results. Overall, studies show that inquiry learning can be a very effective way of learning as long as it is accompanied by an adequate level of prior knowledge and appropriate instructional guidance (de Jong, 2022). In Go-Lab learning environments or ILSs (as the one used in this study),

guidance is present in the form of an inquiry cycle that structures the overall process and with scaffolds for specific inquiry activities within each inquiry phase. An adequate level of prior knowledge can be arranged for by pre-inquiry instruction (prior to the ILS or in its introductory phase). This approach ensures that students have the necessary knowledge to perform inquiry activities adequately, but prior knowledge can also come in the form of naïve understandings or misconceptions. Inquiry learning is often seen as a suitable way to remedy misconceptions because when doing experiments students can be confronted with (wrong) expectations based on their misconceptions, which may stimulate them to adapt their knowledge (Prince et al., 2012). Finding outcomes from experiments that are not in line with a student's (mis)conception can lead to a disequilibrium that students can resolve by adjusting their existing knowledge (Longfield, 2009). Often, however, existing work has assumed that students will be confronted with their misconceptions spontaneously. A recent overview showed that for cognitive conflict to work many conditions should be met (Potvin, in press). In the study we present here, we designed an inquiry environment specifically to bring known misconceptions to the fore. In the ILS that we designed for this purpose, a specific tool, the hypothesis scratchpad was used to present hypotheses invoking the misconceptions, together with two online labs in which these hypotheses could be tested. In addition, students in this condition received a Padlet that supported them in discussing their (evolving) conceptions.

The students in the experimental and control groups had a similar understanding of CM at the beginning of the study. In fact, at the start, all students had misconceptions about CM, especially concerning the direction of the force that causes the motion. After the students in the experimental condition were taught using an ILS geared towards addressing students' potential misconceptions and the students in the control condition were taught using an ILS designed in line with the traditional course outline only, the learners in the experimental condition, controlled for pre-test scores, outperformed the students in the control condition on a knowledge test measuring conceptual understanding of CM.

Discussion and future work

Our results suggest that when activities are tailored towards addressing specific misconceptions, students' inquiry process is more effective. The effect of inquiry activities focusing on inquiry is supported by many other studies that promote the use of inquiry learning approaches (Pedaste et al., 2015; Canlas, 2015, 2016; Ching, 1999; Gunstone, 1984; Husnaini & Chen, 2019). These studies asserted that using teaching approaches that actively involve students in the learning process tends to encourage them more to appreciate the scientific understanding of concepts. The impact of engagement in inquiry by the experimental condition may have arisen from the level of critical thinking that students were involved in, as they were stimulated to question their prior knowledge of the topic.

In this study, we grouped several types of support to be able to use a full design addressing misconceptions. Students in the experimental group received different hypothesis scratchpads and different online labs than the students in the control condition. In addition, their ILS contained a Padlet and a quiz at the end focusing on the alleged misconceptions. Therefore, the effect that the experimental ILS showed cannot

be attributed to one of the specific instructional elements, but rather to their composite. In follow-up studies we can disentangle this effect and see which of the elements gives the largest contribution. To allow for a naturalistic learning setting, we did not control for students' learning time, nor could we measure this. We do not have any indications that this differed between conditions, but time differences may potentially have contributed to the effect of the experimental condition.

This study has shown the potential of designing inquiry leaning environments according to known misconceptions of students. A next step could be to determine which misconceptions each individual student possesses and present the student with assignments addressing only those individual misconceptions (see e.g., Subheesh et al., 2022). Longitudinal research to trace the conceptual change process could also be done. Finally, our results were obtained within the field of CM; future research should investigate whether similar results can be obtained in other science domains as well.

Appendix

Pre-test

- Figure 6 shows two thin curved metal tubes placed horizontally. A small metal ball is put into the end of each of the tubes indicated by the arrows. The balls are then shot out of the other ends of the tubes at high speed. Assume that the balls will come out of the tubes at the same speed. Ignoring air resistance and friction inside the tube, draw the paths the balls will follow immediately after they come out of the tubes.

Explain why the balls move in the paths drawn by you.

- A boy has a metal ball attached to a string and is swinging it at a constant speed in a *horizontal circle* above his head. In Fig. 7 you are looking down on the ball. The circle shows the path followed by the ball and the arrows show the direction of its motion.

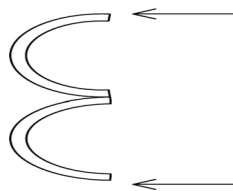


Fig. 6 Thin curved metal ball placed horizontally

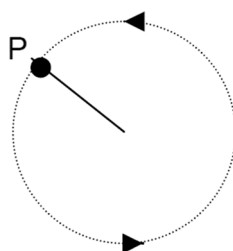


Fig. 7 Metal ball attached to a string swinging in a horizontal circle

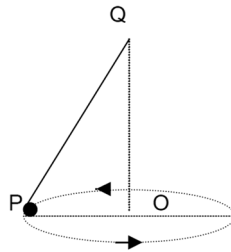


Fig. 8 Model of a metal ball rotating in a horizontal circle

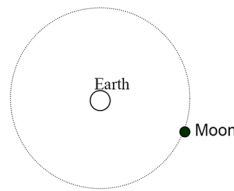


Fig. 9 Model of a Earth and Moon interaction

The line from the centre of the circle to the ball is the string. Assume that when the ball is at the point P, the string suddenly breaks. Ignoring air resistance, draw the path of the motion of the ball immediately after the string breaks. Explain why the ball moves in the path drawn by you.

3. Figure 8 shows a bob of mass 20 g attached to the end of a light and inextensible string of length 48 cm rotating in a horizontal circle of radius 10 cm with a constant angular speed about the vertical. Ignoring air resistance,

- (i) Indicate and label the forces acting on the bob at the point P.
- (ii) Indicate and label the resultant force.

4. The Moon of the Earth is travelling at a constant speed in a circle around it.

- (i) On Fig. 9, draw arrows to represent the forces acting on the Moon. Name the forces.
- (ii) The total force acting on the Moon is

- A. Zero.
- B. Not zero, and in the direction of motion.
- C. Not zero, and in some other direction.

Explain your answer.

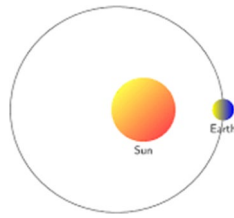


Fig. 10 Model of the Sun and Earth interaction

Post-test

1. A small car and a big truck are moving at the same speed of 100 km/h around a smooth banked curve road. The small car, which has a mass m , negotiates the curve without slipping. The truck, which has a mass of $2.5 m$, will:
 - (a) Also negotiate the curve without slipping.
 - (b) Tend to slide down (i.e., towards the inside of the curve).
 - (c) Tend to slide up (i.e., towards the outside of the curve).
 - (d) None of these.

Explain your answer.

2. The Earth moves in its orbit around the sun at a constant speed of 110,000,000 m/h
 - (i) On Fig. 10, draw arrows to represent the forces acting on the Earth. Name the forces.
 - (ii) The net force acting on the Earth is:
 - A. Zero.
 - B. Non-zero, and in the direction of motion.
 - C. Non-zero, and in some other direction.

Explain your answer.

3. Taonga, Mwansa, and Chipego have approximately the same mass and are riding a merry-go-round that is turning with a constant angular velocity. They are at distances R_1 , R_2 and R_3 , respectively, from the centre of the merry-go-round. The distances are ordered as follows: $R_1 < R_2 < R_3$. Which person will:
 - (a) Experience highest acceleration? Explain your answer.
 - (b) Have the lowest velocity? Explain your answer.
 - (c) Hold on to the merry-go-round most tightly? Explain your answer.
4. Figure 11 shows a bob of mass 20 g attached to the end of an inextensible and light-weight string of length 48 cm, rotating in a horizontal circle of radius 10 cm with a constant angular speed about the vertical.

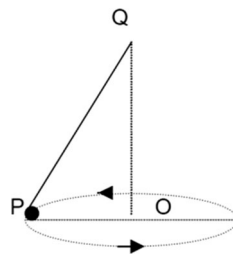


Fig. 11 Model of a metal ball rotating in a horizontal circle

- (i) Ignoring air resistance, indicate and label the forces acting on the bob at point P.
- (ii) Indicate and label the resultant force.
- (iii) Explain the action of the resultant force that you have labelled.

Supplementary Information

The online version contains supplementary material available at <https://doi.org/10.1186/s40561-023-00236-y>.

Additional file 1. Figure 1. Phases of an ILS showing the investigation phase with a PhET simulation1. **Figure 2.** The hypothesis scratchpad as used in the control condition. **Figure 3.** Padlet postings by students. **Figure 4.** Display for the uniform circular motion simulation. **Figure 5.** Box and whiskers plot of pre-test and post-test scores.

Additional file 2. Table 1. Descriptive statistics for the pre-test and post-test (% correct).

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Declarations

Ethics approval and consent to participate

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Consent from the Copperbelt University was sought to conduct and publish the study.

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