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Determining the Intelligibility of Einsteinian Concepts with Middle School Students

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Abstract

The modern Einsteinian conception of space, time, matter and radiation represents a radical paradigm shift compared with the traditional Newtonian physics that underpins most primary and secondary school science. It is increasingly recognised that school education should encompass this modern paradigm to allow a seamless progression of learning throughout school education. The goal of the research presented in this paper was to test whether five core concepts of the Einsteinian paradigm could become conceptually intelligible to middle school students or whether there were intrinsic difficulties. The research was underpinned by the theoretical notion that intelligibility is a key step to the ontological conceptual changes needed for the radical shift to the Einsteinian paradigm and that conceptual change is impacted by students' attitudes. The research was conducted in the context of a 20-lesson teaching programme based on models and analogies specifically designed for middle school students and to enable ontological conceptual change. We present an analysis of 120 14- to 15-year-old students' conceptualisations of Einsteinian physics and their attitudes towards science as a result of this programme. Through testing before and after the programme, we found that the students possessed variable levels of prior knowledge of the core Einsteinian concepts, but near universal intelligibility of the core concepts after the programme. The strong saturation indicates that there is no intrinsic difficulty regarding intelligibility of core Einsteinian concepts at the middle school level of the participants. While the male students initially showed greater interest in physics compared with their female counterparts, the female students showed a significantly increased interest in physics after the programme. Repeatability in knowledge tests between classes given one year apart and long-term retention indicate that the programme had a lasting impact on students' conceptual understanding.

Keywords Einsteinian physics · Models · Analogies · Einstein-First · High school physics curriculum

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Introduction

Our current understanding of the universe is based on two major theories of physics: the theory of gravity, also known as general relativity, and the theory of particle interactions or quantum physics. Because of Einstein's central role in both theories, we use the term 'Einsteinian physics—' to distinguish these subject matters from classical Newtonian physics. Einstein's key ideas include the relativity and warping of time, the curvature of spacetime and the quantisation of radiation (photons), as well as stimulated emission of radiation and Brownian motion (Einstein, 1905a, 1916, 1956). Many other physicists, including Bohr, Planck and Heisenberg, contributed to this paradigm shift in scientific thinking—from Newtonian to so-called modern physics.

Einsteinian physics is of immense importance in modern technology. Communication systems, lasers, transistors, semiconductors, nuclear power and many more of today's technologies are based on Einsteinian physics. However, in many countries, including Australia, the high school science curriculum is focused mainly on Newtonian physics. Einsteinian concepts are generally introduced only as special advanced topics (ACARA 2017; Dimitriadi and Halkia 2012; Shabajee and Postlethwaite 2000). It is often believed that Einsteinian physics is too difficult to introduce to this age group as discussed further below (Pospiech 2008).

The research presented in this paper is part of a broader research movement titled Einstein-First. The Einstein-First research project has been developing and testing approaches to the teaching and learning of Einsteinian physics across the school curriculum. We share Shabajee and Postlethwaite's (2000) motivation that students deserve to be taught our current best understanding of the nature of the universe in which we live. Besides this philosophical standpoint, we suggest that by being relevant to the modern world, learning Einsteinian physics could be expected to improve student attitudes to physics because of its relevance to the modern world.

As part of Einstein-First research project, an initial study introduced a six-lesson programme on Einsteinian concepts to year 6 primary school students. These students clearly enjoyed the programme; the majority claimed (through questionnaires) that they were not too young and indicated no sense of surprise by the Einsteinian physics concepts. However, several of the concepts were clearly not intelligible to many of the participants (Pitts et al. 2014). The second implementation of the in-class programme with academically talented year 11 students indicated that they found the modern concepts exciting and astonishing (Kaur et al. 2017c). As part of Einstein-First, the research presented in this paper was designed to support our quest to find the right age to introduce key Einsteinian physics concepts. As such, the goal of this research was to explore the impact of a 20-lesson teaching programme designed for conceptual change on academically talented year 9 students. In particular, we were interested in the impact of the programme on the intelligibility of five key Einsteinian concepts and the impact on participating students' attitudes towards physics.

This paper is structured into five sections. This first section has provided an introduction to the research. The next section is the "Literature Review", and the third section is the "Methodology". The fourth section of the paper presents the results and the final section, the "Discussion and Conclusion".

Literature Review

In this literature review, we initially present an argument as to why Einsteinian physics needs to be introduced at an early age into the school curriculum. We then develop the theoretical position of conceptual change and an argument based on the available literature about the possible impact of Einsteinian physics on students' attitudes towards science. This is followed by a description of the Einstein-First programme, and the section concludes with a statement of the purpose and objectives of the study.

The Case for Introducing Einsteinian Physics at an Early Age

According to Shabajee and Postlethwaite (2000), Einsteinian physics concepts should be presented at an earlier stage of education. If they are only encountered in the later stages of education, they are likely to be found by learners as obscure ideas that are impenetrable and difficult to reconcile with their perceptions of the world around them and ideas developed through regular physics curriculum (Shabajee and Postlethwaite 2000). Stannard (2008), Emeritus Professor of Physics at the Open University, has continued to argue this case strongly. Previously, Stannard (1999) wrote

> Our first introduction to the mind-blowing world of modern physics should be when we are young, when our minds are still open and flexible. As we become older we become set in our thinking, our view of the world fossilises; we become resistant to new modes of thought.

It is plausible to assume that an earlier introduction of Einsteinian physics concepts may help students to better appreciate the reality of the universe and prepare them to acquire more details on these topics in later studies. Stannard (1999, p. 20) went on to state

> [relativity] is absolutely wonderful, amazing science.... But I was angry that none had told me about it before (undergraduate level). It seemed a scandal that Einstein's theories had been around for so long but were not part of everyday culture.

However, despite the exhortations discussed above, in general, there has been little research on teaching Einsteinian concepts at high school and especially for younger age groups including those in the middle years. Some research has been conducted with university-level students on the teaching and learning of different aspects of Einsteinian physics, for example, special relativity, general relativity and quantum physics. These approaches include simulations and computer games (Carr and Bossomaier 2011; Carr and McKagan 2009; Wegener et al. 2012), thought experiments, the use of paradoxes (Cacioppo and Gangopadhyaya 2012; Velentzas and Halkia 2013), physical models (Zahn and Kraus 2014) and various online learning resources (Henriksen et al. 2014). Previous research has shown that many students have the ability to understand qualitative concepts of Einsteinian physics (Baldy 2007; Pitts et al. 2014). In Australia, for example, research has shown a significant improvement in students' understanding and interest in Einsteinian ideas. Haddad and Pella reported that year 6 students could understand the concepts of relativity at an appropriate knowledge level (Haddad and Pella 1972). Johansson and Milstead said that introduction of the uncertainty principle helps students to understand the mysterious nature of quantum mechanics (Johansson and Milstead 2008).

Research has also identified many of the misconceptions and difficulties associated with the learning of Einsteinian concepts. Dimitriadi and Halkia (2012) discussed difficulties in students accepting that the speed of light is the maximum speed in the universe, as well as difficulties in conceptualising the relativity of time and the absence of absolute reference frames. Bar et al. investigated difficulties in forming a valid concept of gravity (Bar et al. 2016). Junius (2008) explored difficulties in conceptualising the idea of a straight line when space is curved. With regard to quantum physics, Ozdemir and Mustafa (2010) emphasised the difficulties for undergraduate students to conceptualise the probabilistic nature of quantum physics, while Sokolowski (2013) investigated difficulties in understanding the photoelectric effect. These difficulties have deterred the introduction of modern physics at an early age.

Most research has focussed on undergraduate teaching and identified students' misconceptions and difficulties in understanding the concepts of Einsteinian physics. This appears to have created the idea that young students, particularly those of middle and primary school age, are not able to be taught Einsteinian concepts. There is very limited research on the teaching and learning of Einsteinian physics at an early age. As such, the research presented in this paper makes a significant contribution to the literature by providing evidence about conceptual understanding and attitudes of students when they are being taught about Einsteinian concepts.

Theoretical Position for Teaching and Learning Einsteinian Physics

The challenging situation described above can be best understood and interpreted by the construct of conceptual change which is recognised as a viable and powerful framework to investigate student learning in physics as well as in the design of instruction (Duit and Treagust 2003, 2012). Numerous research studies have shown that students come to science classes with ideas about the phenomena and concepts to be learned that are not in harmony with science views and which are firmly held and resistant to change (Duit and Treagust 2003; Duit et al. 2013).

From the initial research in the late 1970s that took an epistemological view of conceptual change with a focus on students' better understanding of phenomena through learned concepts being plausible, intelligible and fruitful, researchers such as Pintrich, Marx and Boyle (1993) and Zembylas (2005) argued that conceptual change should address the affective domain including attitudes to and enjoyment of science. Another focus on conceptual change argued by Chi (see Chi 2008; Chi et al., 1994) is that for conceptual change to occur with certain science concepts, students need to switch ontological categories. An example would be the switch from the calorific concept of heat to one involving particle motion. In an effort to examine science learning from a more holistic perspective, Tyson et al. (1997) considered learning from a multi-dimensional position that takes into account epistemological change, affective change and ontological change.

In the research described in this article, we were particularly interested in students being able to change their conceptions from a Euclidean or Newtonian view of physics to a relativistic, Einsteinian one. We recognise that students will already have experienced a Euclidean or Newtonian view of the world and hold such an ontology. Our goal was to challenge this ontology at an early age, while minds are still flexible, by introducing students to a relativistic, Einsteinian ontology which they could understand, to determine whether students are able to retain these newly introduced conceptions and to provide motivational and enjoyable learning experiences.

The tables below summarise the core conceptual differences between Newtonian and Einsteinian physics (Table 1) and some of the derived concepts that arise from them (Table 2). The Einstein-First programme aims to enable all people to become comfortable with the Einsteinian concepts, that is, to enable these concepts to be intelligible to them, because they represent our best understanding of the universe.

Table 1 Comparison of the core concepts of Newtonian and Einsteinian physics

Newtonian physics	Einsteinian physics
Space is described by Euclidean geometry	Space is non-Euclidean
Space is an absolute conceptual grid	Space is deformed by matter
Time is absolute	Time changes due to proximity to masses and with relative speed
Light is a wave	Light is a stream of photons
Objects can move at any speed	The universe has a limiting speed equal to the speed of light and the speed of gravity
Gravity is a force created by masses	Gravity is a manifestation of warped time and curved space

Table 2 Some derived concepts in Newtonian physics and their Einsteinian counterparts

Newtonian physics	Einsteinian physics
Geometrical formulae for areas and perimeters are exact	Most useful geometrical formulae are approximations
Parallel lines never meet	Parallel lines can meet
Time is the same everywhere	Time depends on height above the Earth and speed of motion
You can see things without disturbing them	Measurements with light cause uncertainty
Space cannot sustain ripples	Ripples of space travel at the speed of light

Attitudes to Science and Physics

In Australia, students' attitude towards science and the number of students studying science are decreasing (Potvin and Hasni 2014; Hassan 2008). There are many factors suggested by the researchers which influence students' attitudes towards science education. The most common are teaching methods, teaching environment, relevance and utility of science, motivation towards science, enjoyment of science, attitudes of friends or classmates, curriculum, gender and year level (Hassan 2008; Murphy et al. 2006; Nieswandt 2005; Osborne et al. 2003; Pell and Jarvis 2001; Sheldrake et al. 2017).

An effective teaching environment and teaching method has a positive impact on students' attitude towards science (Blazar and Kraft 2017). Researchers have identified the benefits of experiments using simple materials that help students reflect on natural phenomena and that such activities enhance their cognitive skills (Eren et al. 2015; Koç and Böyük 2012; Ornstein 2006).

Studies on gender differences in attitudes towards science, and physics in particular, have shown that at the end of primary education, both genders have positive attitudes towards science, but towards the end of secondary education, a significant decline in females' attitude occurs (Reid 2003). Miller et al. (2006) reported that high school appears to be a critical time for addressing gender differences in attitude to science. Reid observed that females' interests were more inclined towards subjects related to social or daily life whereas their male counterparts showed interest towards mechanical relevance and discussed the importance of creating a more balanced physics syllabus. Lorenzo et al. (2006) and Pollock et al. (2007) found that active pedagogies or in-class interactions might help to reduce the gender gap in attitude towards science.

Numerous studies reflect the widespread concern about declining student attitude towards science. Our proposition is that introducing modern physics to school students may improve their attitudes towards physics and science generally. In the research presented in this paper, we were interested in investigating the impact that teaching Einsteinian physics concepts, which combines active learning with in-class interactions, has on students' interest in physics.

Evaluation and Approach to Learning

There is much evidence that tests can be effective tools for assessing students' conceptual understanding as well as improving their learning (Roediger and Karpicke 2006). Chang et al. mentioned in their study that "tests have been regarded as not only an important means for assessment, but also an influential method for developing students' conceptual understanding" (Chang et al., 2010). Previous research has shown that the use of models and analogies in the learning and teaching process helps students to engage in learning and to develop conceptual understanding of a particular topic (Heywood 2002; Ogborn et al. 1996). According to Posner et al., for conceptual change in students' understanding, a new conception should be understandable, believable and provide new possibilities or ideas (Posner et al. 1982). Treagust et al. suggest that students need to use their prior knowledge and ideas to make judgements in new conceptions (Treagust et al. 1996).

The programme discussed here makes extensive use of models and analogies as teaching strategies explicitly because of their power to make abstract concepts understandable and believable and because they are consistent with activity-based learning and group activities.

The Einstein-First Programme

The Einstein-First project is underpinned by a constructivist epistemology and a conceptual change approach to pedagogy. Active learning was used to explore ideas that begin with geometry and gravity and conclude with quantum physics. Each lesson involved students in group activities, and was strongly based on the models and analogies described in Kaur et al. (2017a, 2017b). Group activities were chosen to allow students to learn by interacting with each other, and by discussions (Michael 2004). This also allows students to share roles of measuring, manipulating and recording.

In "Theoretical Position for Teaching and Learning Einsteinian Physics" section, we summarised the conceptual differences between Newtonian and Einsteinian physics highlighting the ontological shift that would be required to move conceptually between these paradigms. Here, we provide a more complete discussion of the origin of the new conceptual framework in the context of the implementation of our Einsteinian physics lessons. Detail of the practical implementation of the learning materials can be found in Kaur et al. (2017a, 2017b).

Euclid's book of geometry *Elements* is said to be the most influential book of all time, continuously in print for 2000 years and published in more than 1000 editions (Gibson 1927). The findings of Euclid's geometry were believed to be factual statements about the real world until first questioned by Gauss in the early nineteenth century (Halsted 1990). Experimental proof of Einstein's general relativity from 1919 to the present day, including the recent direct detection of gravitational waves, has relegated Euclidean geometry to a useful approximation because real space is not Euclid's flat space. This means that all geometric formulae such as the perimeter of a circle or area of a rectangle are approximations. These ideas are easily explored by studying geometry on curved surfaces. Thus, our programme replaces theoretical geometry with experimental geometry on curved surfaces in which students can draw their own conclusions. For example, we use magnetic posts on upturned woks to survey straight lines and test geometrical formulae for perimeters and angles (see photos and more extensive discussion by Kaur et al. (2017a)).

Newtonian physics is based on the concept of absolute space and time, the assumption that space, time and matter are independent of each other and that gravity propagates instantaneously. Einstein's theory of gravity links space, time and matter. A key idea in relativity is the existence of an absolute speed limit in the universe, which is the speed of light, and as dramatically proved in 2017, is also the speed of gravity (Abbott et al. 2017).

Our Einstein-First programme seeks to introduce the above fundamental concepts before the alternative and obsolete Newtonian concepts have been firmly fixed in student minds. The speed limit of the universe concept is developed through activities and thought experiments based on the concept of terminal velocity. We use the free fall of balloons weighted with small amounts of water as a physical model. Students measure the free fall using smart phones with frame-by-frame analysis to allow the plotting of height versus time. The relativity of space, time and geometry in Einstein's theory of general relativity can be very powerfully taught using space-time simulators in which stretched fabric mimics the curvature of space. These devices provide a useful framework for exploring the rich diversity of gravitational phenomena using enjoyable interactive experiments (Kaur et al. 2017a), with extra insight provided through criticism of the shortcomings of the model.

The quantum nature of explanation of the light and matter followed Planck's recognition of the need for quantising energy (Planck 1901) and Einstein's photoelectric effect (Einstein, 1905b). The millennia-long debate on the nature of light was resolved with the development of quantum optics in the twentieth century. In this time, we learnt that all matter have wavelike properties and that electromagnetic waves are quantized and are only detected as particles. In our programme, we explore these concepts using many of the ideas of Nobel Prize-winning physicist Richard Feynman who stated "*I want to emphasise that light comes in this form – particles. It is very important to know that light behaves like particles, especially for those of you who have gone to school, where you were probably told something about light behaving like waves*" (Feynman 1985, p. 15).

We use models and analogies again to explore quantum concepts. We use toy photons and explore how their momentum can cause 'quantum uncertainty' when used to measure the position of a balloon. We use videos of single photons creating images one photon at a time to emphasise that all optical imagery arise when a multitude of photons combine to create seemingly continuous images. With the help of toy photons, we allow students to discover that the photons in the stream reaching their eyes when one looks at a dim star are of order 1000 km apart. This leads immediately to recognition of aspects of 'quantum weirdness' that would normally be beyond the reach of high school students.

An important aspect of the Einstein-First programme is the linking of toys and models to easily accessible real images of observed physics such as single-photon imaging and physical phenomena such as Google images of gravitational lenses, which are manifestations of curved space. We also use Google Earth images of diffracting and interfering ocean waves.

The concepts that the students are led to embrace are rather simple, such as the facts of curved space, warped time and photons. If students can grasp these concepts with ease, we would expect our testing to show very high scores. Only if these fundamental concepts are innately difficult to comprehend (for example, if our brains are somehow intrinsically Newtonian and it takes exceptional intelligence to comprehend them) will students score low in our testing. We were searching for a saturation effect in our testing, because this implies the universal intelligibility of the new concepts.

We use an analogy to illustrate this important point. If all students had been taught that the Earth is flat, and we provided photographic evidence that it is actually spherical, we would expect *all* students to agree to this fact, unless the idea of sphericity for a planet was somehow beyond normal children's comprehension. However, we might expect that some old people presented with the same evidence could claim that the data was faked. Our testing is designed to determine whether there is any significant impediment to children's comprehension of Einsteinian concepts.

Our work is based on the contention that

(a)It is possible to learn/understand/teach the modern Einsteinian paradigm at a young age using appropriate teaching materials.

(b)Student attitudes to physics will improve if they learn modern concepts before being introduced to the useful tools and approximations of Newtonian physics.

As stated above, we also recognise that any changes in attitude we observe cannot be solely attributed to the content, because by necessity we must use teaching approaches that have quite separately been shown to promote positive attitudes to learning.

Purposes of the Study

The purposes of this research were threefold: (a) to assess the impact on two classes of year 9 students of a 20-lesson programme in terms of the intelligibility of Einsteinian concepts, (b) to find out how students' attitudes, including the attitudes of girls and boys, changed as a result of the programme and (c) to investigate retention 1 and 3 years after the programme.

Research Objectives

In particular, the objectives of this study were to discern the following:

1. What the students' conceptual understandings of Einsteinian physics were before and after the programme.
2. What the students' attitudinal response towards physics was before and after the programme.
3. If there was any difference in students' response in terms of their gender.
4. The degree of student retention 1 and 3 years after the programme.

The approach taken to addressing these objectives is described in detail in the next section, the "Methodology".

Methodology

This section outlines the methodology of the research, including the conceptual and attitudinal questionnaires used for data collection, the student sample and the structure of the Einstein-First programme. We also provide details of the data analysis and the validity and reliability of the questions.

The Study

The Einstein-First teaching and learning programme that is the focus of this research consists of 20 lessons with activities, worksheets and questionnaires. In this study, four questionnaires were developed by the researcher. These questionnaires were developed through the process described below.

Conceptual Pre-Questionnaire

This questionnaire, consisting of nine short and multiple-choice questions, was given at the start of the programme; it was designed to assess the students' prior knowledge of the five relevant Einsteinian concepts (see Table 5). The questionnaire focused on the students' understanding of curved spacetime, geometry on curved space, gravity, light and the uncertainty principle. The typical examples of questions we asked are as follows:

- *What do you mean by the term 'light'?*'. In this case, it was made clear that we were not referring to light as opposed to heavy. In each case, we asked for a one to two-line response.
- *Can parallel lines ever meet? Yes or No?. Please explain your answer.*' This is a question of physical fact, and the answer is not influenced by reference frames.
- *Can the sum of the angles in a triangle be different from 180 degrees? Yes or No? Please explain your answer.*'

In all cases, we were not trying to grade the students' depth of understanding but, as discussed in "The Einstein-First Programme" section, we were trying to assess whether there are intrinsic difficulties for students to understand concepts, which for adults are much more difficult because most adults have a deeply engrained concept of Newtonian reality.

Our question about geometry is equivalent to asking a person whether the Earth is roughly spherical or flat, as discussed in "The Einstein-First Programme" section. Only one answer is correct, and it is independent of coordinate systems or mathematical models. If a person has seen photographs and movies of the Earth from space, then independent of talent, coordinate systems, etc., they will know without a shadow of doubt which is the correct answer. In regard to the specific question we asked, modern observations of space tell us that no triangle ever has a sum of angles exactly equal to 180° except in an abstract mathematical space. Of course, we also teach students that on Earth most of the time, the abstract approximation is an extremely good one. Discussion of the pre-questionnaire findings is presented in the "Results" section below.

When participating students had completed the conceptual pre-questionnaire, it was marked by the primary researcher and first author of this paper. Two marks were given to students who gave a correct yes/no answer that included a correct justification. One mark was assigned to those who chose the correct yes/no answer without explanation. One mark was given for a correct short answer or a correct multiple-choice response, and zero marks were given for no response, or an incorrect or unsure response.

Conceptual Post-Questionnaire

The conceptual post-questionnaire was administered to participating students at the end of the programme, and was designed to assess any conceptual change after having participated in the programme. The pre- and post-questionnaires had identical questions and were marked using the above criteria.

Attitudinal Pre-Questionnaire

The attitudinal pre-questionnaire consisted of nine questions (see Table 6), and was designed to assess the students' general attitude towards physics. All responses were based on a Likert scale (strongly disagree to strongly agree). The Likert scale marks were quantified on a 1–5 scale, normally one for strongly disagree and five for strongly agree but reversed where necessary.

Attitudinal Post-Questionnaire

This questionnaire had identical questions to the pre-questionnaire and was designed to observe any change in the students' attitude towards modern physics. This questionnaire was marked using the scale given above.

Views on Einsteinian Programme Post-Questionnaire

A set of five questions requiring short responses was developed to determine the students' views on Einsteinian physics (see Table 7). This questionnaire was only given at the end of the programme.

Delayed Retention Test

A set of nine questions was designed to assess the students' retention of Einsteinian concepts (see Table 8). This was administered one year after the programme with one class and three years after the programme with another.

Each questionnaire was distributed at the start of a standard teaching period before and after the programme, and students were given 20 min for completion. The same questionnaires were used in both the 2013 and the 2014 studies.

The Structure of the Programme

The 10-week programme included 20 lessons, each one structured with carefully designed models and analogies to assist with students' understanding. Generally, the lessons were structured according to the following format:

1. The first 15 min of each lesson was dedicated to introducing and presenting material for the lesson,
2. The next 15 min were devoted to group activity,
3. The last 15 min were for class discussion and the completion of worksheets.

The lesson plans were designed with the intention of making Einsteinian physics interesting and engaging for students of varying academic abilities. The activities and materials that supported this programme are described by Kaur et al. (2017a, 2017b). As summarised in The Einstein-First Programme section, they included lessons using woks and magnetic posts for studying curved space geometry, a lycra sheet space-time simulator for studying gravity and curved space effects, toy 'photons' based on Nerf guns for studying the particle nature of light, water balloons for studying the concept of terminal velocity for developing the concept of the speed limit of the universe as well as the universality of free fall and laser experiments for diffraction and quantum interference supported by videos of single-photon interference.

Student Sample

The sample of students consisted of 120 year 9 students from Shenton college in Perth, Western Australia. They belonged to a selective academically talented programme, but most had not encountered Einsteinian concepts prior to the study except for what they may have learnt through popular media. The programme was run in the years 2013 and 2014. In 2013, 24 male and 21 female students participated, while in 2014, 33 male and 24 female students took part in this programme. The final sample of this study consisted of 102 students due to a few incomplete questionnaires. The group reduced to about half for the retention tests undertaken in 2014 and 2017.

Data Analysis Procedures

Data were processed using Excel to obtain means, standard deviations, etc. A paired sample *t* test was used to evaluate any difference in the students' conceptual understanding after the programme. To analyse attitudinal pre-/post-questionnaires, we combined data for positive responses according to the Likert scale given above. Some of the results were verified using SPSS.

Validity

Validity is defined as the degree to which test scores precisely measure the proposed idea. The validity of the conceptual and attitudinal questionnaires was investigated under the following three questions:

(a)Do the questions encompass every topic we wish to teach the students and have these topics been addressed in the literature?

(b)Are the students able to interpret the questions as they are meant?

(c)Do educational experts agree that the questions are appropriate?

An extensive review process described below was used to ensure validity.

Content and Literature Validation

In designing the conceptual and attitudinal questionnaires, we took the approach that the assessment of students' learning and attitude should be based on the topics we covered in the specially designed programme. Only content-related questions were asked. As discussed in "The Case for Introducing Einsteinian Physics at an Early Age" section, there has been very little research on the teaching of the fundamental concepts of Einsteinian physics. Hence, it is not surprising that some of the conceptual questions have not been previously reported. For both the conceptual and the attitudinal questionnaires, we found three of the nine questions in the existing literature (Pitts et al. 2014; Soh et al., 2010).

Student Interpretation Validation

The language of the questions needed to be simple and clear so that the students would interpret questions as asked. As discussed in "The Study" section, some of the questions such as "Does space have a shape?" and "What is light?" were naturally ambiguous, but the ambiguity was explained to the students so that they understood, for example, that light was not the opposite of heavy and that space referred to the space between your hands or the space of the classroom, rather than outer space. The questions used were directly related to topics covered in the programme.

Expert Validation

Draft questions were reviewed by the authors who include experienced physicists and educators. Each question was discussed and refined. The conceptual questions were reviewed in relation to a large database of physics questions. All questions were redrafted and reviewed a second time before finalising for use in this study.

Reliability

For all student questionnaires, we used internal consistency as a measure of reliability. In order to investigate the internal consistency, we used Cronbach's alpha (Cronbach 1951). The values of Cronbach's alpha for various tests are given in the Table 3.

The calculated values of Cronbach's alpha indicate that all the questions are highly reliable. The following section presents the results obtained from the questionnaires.

Table 3 Cronbach's alpha for all the questionnaires used in this study

Questionnaire	Cronbach's alpha
Conceptual questionnaire	0.91
Attitudinal questionnaire	0.89
Views on Einsteinian programme post-questionnaire	0.88
Delayed retention test	0.88

Results

In this fourth section, we first present the students' results from the conceptual pre-/post-programme questionnaires, followed by the attitudinal pre-/post-results. Finally, we discuss the results from the retention testing.

We shall now discuss the findings from each of the two 20-lesson programmes. The first programme was introduced in 2013. In 2014, the lesson plans and activities were refined. The skills of the presenter Tejinder Kaur had significantly improved in 2014 through the experience of the first year. There was one additional difference between the programmes in 2013 and 2014. In 2014, students undertook a mid-programme test which may have helped to reinforce their learning.

We first present an overview of results for conceptual learning before giving more detail. We divided the test scores into three bands: low achieving (0–40%), mid range (40–80%) and high achieving (81–100%) as shown in Table 4. These are presented separately for each year of the programme. Results highlight the high level of learning achieved, especially in the second year. The individual questions are presented below, where we analyse results for each question.

In the second year, 88% of the students were in the high-achieving band. It is also interesting to note that the standard deviation (SD) between the pre- and post-tests reduced from 17.5% to 12.6% in 2013 and 14.6% to 10.3% in 2014 despite the increased mean scores. This implies again that the uptake of the concepts was independent of the pre-test score, a fact that is obvious by inspection of Fig. 1a, b. Below, we discuss details of the 2013 results, followed by the 2014 results. In an attempt to understand some of the higher scores obtained in knowledge pre-test, we asked the classes where they had learnt Einsteinian concepts. Most indicated that they had learnt from the internet or TV.

Students' Overall Results in Conceptual Learning from 2013 (Objective 1)

Figure 1a presents the results of 45 students who completed their pre- and post-questionnaires conducted in 2013. Results are presented in the ascending order of score in the pre-test. In the pre-test, 93% of students scored less than 50%. Just 11 students scored more than 40% in the pre-test. This may reflect some prior knowledge as discussed above. However, we noted that none of these students gave a response to the requested explanations against the five yes/no answers in the questionnaire.

The highest score achieved in the pre-test was 65% by student number 45. After the programme, this student achieved a 100% score, as did student number 30. In the post-test,

Table 4 Students' statistical results from 2013 and 2014 on the conceptual pre-/post-questionnaire

Distribution of scores	Percentage of students (2013)		Percentage of students (2014)	
	Pre	Post	Pre	Post
Low range (0–40%)	76%	0%	91%	2%
Mid range (41–80%)	24%	80%	9%	10%
High range (81–100%)	0%	20%	0%	88%
Mean	27%	73%	23%	91%
SD	17.5%	12.6%	14.6%	10.3%
Paired *t* test	$t(44) = 20.1$		$t(56) = 30.3$	
Effect size, *d*	3		5.5	
Results	Statistically significant		Statistically significant	

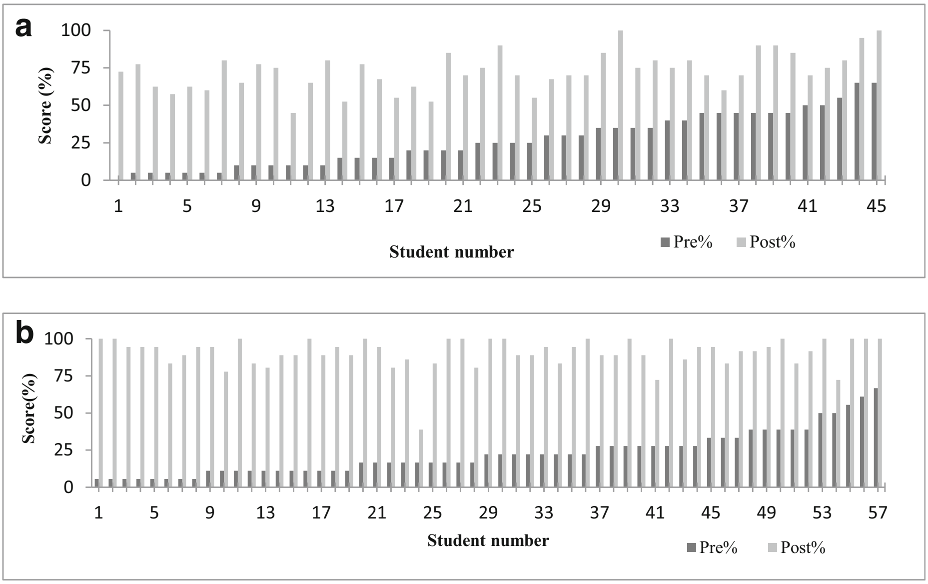

Fig. 1 **a** Conceptual understanding test results for 2013. The histogram, ranked in order of the pre-test score, shows that almost all students achieved a high level of conceptual understanding, independent of their pre-programme understanding which was generally low. **b** Conceptual understanding test results for 2014. The data in **b** clearly shows similar behaviour to that obtained in the previous year, but notably the post-test results are significantly higher

only one student (student number 11) scored less than 50%. The 13 students who scored less than 10% in the pre-test increased their mean score to 68%. The 11 students who scored more than 40% in the pre-test achieved a mean final score of 81%. Thus, the top achieving scores in the post-test are weakly correlated with the scores in the pre-test, while overall the post-test score is relatively uniform. No student showed a decreased score indicating that all students improved their knowledge of Einsteinian concepts. The significance of the improvement is clearly statistically significant.

The results of the pre- and post-conceptual test scores and paired sample *t* test analyses demonstrated that the participating year 9 students had developed a better conceptual understanding by the end of the programme. We also found that the improvement factor for female students was 2.4 (pre-test mean = 31, post-test mean = 73), while for males, it was calculated as 3.3 (pre-test mean = 21, post-test mean = 70).

Students' Overall Results in Conceptual Learning from 2014 (Objective 1)

The findings from the pre-/post-questionnaires in 2014 are presented in Fig. 1b, following the format of Fig. 1a. First, it is interesting to note that the distribution of initial scores is similar to that of the class of 2013. However, it is also clear from this data that the post-test results are overall significantly higher.

Eight students who scored less than 10% in the pre-test increased their mean score to 94%. This exceeds the mean score of the class, and is consistent with the evidence from 2013, indicating that the learning outcomes are rather independent of student prior knowledge. Interestingly, the two students (student numbers 1 and 2) who had the lowest scores in the pre-test achieved 100% in the post-test. The five students who scored more than 40% in the pre-test achieved a mean final score of 94%. In comparison in 2013, 11 students in this category achieved 81% in the post-test and only one student scored below 50% (student 24) in the post-test.

The paired sample *t* test analyses demonstrated the year 9 students, $t(56) = 30.3$, $p < .05$ and Cohen's $d = 5.5$, indicating that conceptual understanding improved after the Einsteinian physics programme. In 2014, the improvement factor for female students was calculated as 4.3 (pre-test mean = 22, post-test mean = 94) and for males 3.8 (pre-test mean = 23, post-test mean = 88).

In both years (2013 and 2014), it was seen that the overall gains for conceptual understanding were large. The large gains are not surprising because the programme represents the students' first introduction to the content, so their pre-instruction scores were low. The saturation effect that is especially strong in the 2014 post-test scores is a measure of the success of the programme. If we did not observe a saturation effect, we would have to conclude that only some students can be fully comfortable with the Einsteinian concepts presented. The saturation effect tells us that there is no evidence that it requires special academic talent to appreciate Einsteinian concepts. It could be argued that the saturation observed represents a poorly designed test, which would be valid if we were trying to distinguish talent levels. However, as a measure of successfully imparting an Einsteinian conception of reality, we argue that it demonstrates that the learning of Einsteinian concepts has no intellectual or cognitive barriers.

The regression analysis of conceptual understanding for both years is provided in Fig. 2.

The data in Fig. 2 present pre-test scores plotted against post-test scores for each student in the programme. It is clear in the figure that the results improved for the revised programme in 2014. The data show a strong saturation of post-test scores indicating that the conceptual understanding as measured by the post-test is unrelated to prior knowledge. Also, there is a weak correlation observed between pre- and post-test scores in both years.

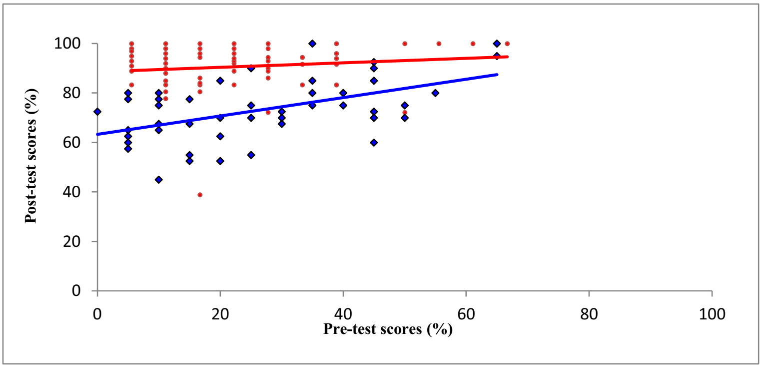

Fig. 2 Students' overall scores in pre- and post-tests in both years. The blue diamonds represent students' scores in 2013, while orange circles are the results for 2014. It is clear in the figure that a high level of learning was achieved, especially in the second year. For the visibility of all data points, the overlap points were shifted ±2.5. The trend from both years shows that there is a weak correlation between pre- and post-scores (the value of r^2 in 2013 is 0.27, and in 2014, it is noted as 0.017) (colour figure online)

Analysis According to Each Question (Objective 1)

In Table 5, we show the scores obtained from the conceptual pre-test and post-test for the entire cohort of students over both years, for each of the nine conceptual knowledge questions. The general improvement in student knowledge as already summarised in Table 4 is apparent, but there is also significant scatter. Two questions (conceptual questions (CQ) 5 and 7) stand out with higher pre-test marks. We will discuss the reasons for this below. Also, two questions (CQ 3 and 9) yielded very low marks. Analysis of individual answers showed that, for the first question, students understood light as something that allows you to see or remove darkness, without having any sense of its nature. Students had no pre-knowledge that light is either an electromagnetic wave or a stream of photons. The second question relates to a much more sophisticated concept—the quantum uncertainty principle—for which the low score is not unexpected.

Table 5 shows students' result for each question before and after the programme. The results show that students improved their conceptual understanding for every concept after the programme. The maximum improvement was seen in the concepts of experimental geometry CQ 1 and CQ 2 for which the post-test score was 100%.

Questions on Curved Space Geometry: CQ 1, CQ 2, CQ 4 and CQ 6

Questions CQ 1, 2, 4 and 6 were designed for testing students learning about curved space geometry. This topic was taught through a range of activities:

(a)Trajectories of toy cars: To see that parallel lines can meet, students studied trajectories of cars without steering, so always moving straight, on a curved elastic membrane.

(b)Experimental geometry on woks: Students had learnt experimental geometry by drawing triangles of different sizes on woks (cooking utensils) with lines defined in straightness by lining up magnetic posts. They found that the sum of the angles of a triangle is not equal to 180° on curved surfaces, and only approximating 180° for very small triangles.

(c)Straight lines on a curved surface: Students had learnt how we could define straightness using laser light, or a tightly stretched string on a curved two-dimensional surface, to determine the shortest distance between points.

Table 5 Average students' correct results for each question before and after the programme

Conceptual question (CQ)	Questions asked in the pre-/post-test	Pre-test (%)	Post-test (%)
1.	Can parallel lines meet?	15	100
2.	Can the sum of the angles in a triangle be different from 180 degrees?	17	100
3.	What do you mean by the term "Light"?	3	92
4.	Does space have a shape? Circle Yes or No. How could you measure the shape of space?	34	90
5.	If you weighed an object on a supersensitive balance, would the balance register a different weight if you heated the object up?	47	82
6.	How could you tell if a ruler is straight?	26	73
7.	In the absence of air resistance, (like in a huge vacuum tank or on the Moon) if we drop a hammer and a feather, which one of them will touch the ground first?	66	100
8.	List the names of at least four types of electromagnetic radiation.	30	81
9.	A person claims on Facebook that he has made a perfect microscope that is so accurate that the exact position of an atom can be measured. Could this claim be plausible?	4	80

The mean scores of CQ 1, 2, 4 and 6 were 100%, 100%, 90% and 73% respectively. Clearly, students achieved excellent understanding of curved space geometry.

Question on Mass-Energy Equivalence: CQ 5

Question CQ 5 was chosen to test student learning about the equivalence of mass and energy: $E = mc^2$. There were two parts to this question, yes or no and an explanation. In the pre-test, almost all students answered yes, but failed to give any explanation. We are surprised by this result because there is little public awareness of this subtle effect on mass caused by the presence of the thermal energy. In the lessons, this concept was taught. Specifically students had been asked to calculate the increased mass of a phone battery when it is charged. The 82% mean in the post-test indicated significant understanding of this concept.

Question on Free Fall: CQ 7

Question CQ 7 on free fall is a topic that is quite widely covered in space media, for example a beautiful BBC video by Brian Cox on free fall in a NASA vacuum tank and video from the Apollo Moon landing. Thus, the high pre-test score is not surprising. Having undertaken free-fall experiments during the programme, students scored 100% in the post-test.

Questions on Light and Electromagnetic Waves: CQ 3 and 8

Questions CQ 3 and 8 were designed to test student understanding of the nature of light and electromagnetic waves. As already discussed, in the pre-test, students demonstrated minimal knowledge of the physical nature of light, as indicated by the CQ 8 score. Following the programme, they had learnt that light is an electromagnetic wave with a dual nature (wave/particle duality). To study the wave nature of light, students undertook simple interference experiments. To understand photons, we used small plastic projectiles to mimic photons so that they could study an analogue of the photoelectric effect (Kaur et al. 2017b). After the programme, 92% of the students were able to correctly describe the nature of light (CQ 3) compared to an initial 3%.

Question on the Uncertainty Principle: CQ 9

Question CQ 9 was intended to test understanding of uncertainty principle which makes a perfect microscope impossible. Students had learnt about this using ‘Nerf gun photography’ in which they had observed the disturbance of a balloon which was impacted by Nerf gun photons. They had learnt that photons disturb the objects they measure. The 80% post-test score shows that most students had grasped this concept.

Attitude Questionnaire (Objective 2)

A questionnaire consisting of nine questions, listed in Table 6, was given to the students to evaluate their attitudes towards physics. As explained above, the questionnaire employed a five-point Likert scale and the students were asked to rate identical questions before and after the sessions. First, we present the overall analysis for the attitudinal questionnaire pertaining to the whole class in both 2013 and 2014. To examine whether there was a significant difference

Table 6 The set of attitudinal questions used in the pre- and post-questionnaires in 2013 and 2014

Attitude question (AQ)	Attitudinal questions asked in pre- and post-questionnaires
1.	I think physics is an interesting subject.
2.	I prefer to learn physics through hands-on activities.
3.	I enjoy learning new concepts and ideas.
4.	I enjoy trying things out at home and/or telling my family about school science activities.
5.	I think hands-on activities help me understand and remember new ideas much better than if they are just from books and formal lessons.
6.	The things that Einstein discovered are important for modern technology.
7.	I like doing mathematical calculations.
8.	Understanding scientific ideas is more important than just memorising facts.
9.	I enjoy science excursions and would like to have more of them.

in students' attitude before and after the programme, a *t* test was conducted to compare both the mean pre-test score and mean post-scores. The results are given in Table 7.

For gender analysis, the results from the two years (i.e., 2013 and 2014) were combined to give a total questionnaire population of 102 students comprising 57 males and 45 females. For this analysis, the positive answers ('agree' and 'strongly agree') were combined and expressed as a percentage of the population. We examined two factors in analysing the answers. The first was to determine the general attitude of the students towards physics. Secondly, we examined any changes in the students' responses before and after undergoing the programme. We analysed the answers relating to the questions by dividing them into four categories, which are explained in the following paragraphs.

Table 7 Attitude statements, attitude test means and statistical significance acquired from paired sample *t* tests

Attitude statements	2013 ($n = 45$)			2014 ($n = 57$)		
	Pre-test mean	Post-test mean	*t* value *p* * value	Pre-test mean	Post-test mean	*t* value *p** value
I think physics is an interesting subject	3.9	4.2	$t = 4.46$ $p < 10^{-2}$	3.9	4.1	$t = 3.51$ $p < 10^{-2}$
I prefer to learn physics through hands-on activities	4.1	4.1	$t = 0.57$ $p = 0.57$	4.1	4.0	$t = 1.94$ $p = 0.06$
I enjoy learning new concepts and ideas	3.9	4.2	$t = 4.23$ $p < 10^{-2}$	4.1	4.2	$t = 1.43$ $p = 0.159$
I enjoy trying things out at home and/or telling my family about school science activities	2.9	3.4	$t = 7.42$ $p < 10^{-2}$	3.1	3.4	$t = 4.47$ $p < 10^{-2}$
I think hands-on activities help me understand and remember new ideas much better than if they are just from books and formal lessons	4.2	4.3	$t = 1.35$ $p = 0.18$	4.3	4.2	$t = 2.57$ $p = 0.12$
The things that Einstein discovered are important for modern technology.	4.3	4.2	$t = 1.43$ $p = 0.16$	4.0	4.5	$t = 7.09$ $p < 10^{-2}$
I like doing mathematical calculations	2.7	3.1	$t = 5.42$ $p < 10^{-2}$	3.1	2.9	$t = 3.09$ $p < 10^{-2}$
Understanding scientific ideas are more important than just memorising facts	4.1	4.3	$t = 3.54$ $p < 10^{-2}$	3.9	4.2	$t = 4.81$ $p < 10^{-2}$
I enjoy science excursions and would like to have more of them	4	4.3	$t = 4.45$ $p < 10^{-2}$	4.5	4.3	$t = 2.88$ $p < 10^{-2}$

*$p \leq 0.05$

The questionnaires were designed to be suitable for average students. Our academically talented science specialist students at a top high school clearly entered the programme with positive attitudes to science, evident interest in hands-on activities and knowledge of the importance of Einstein. This led to loss of resolution for some of the questions. For this reason, we analysed individual questions and gave emphasis only to questions where significant effects were observed in both 2013 and 2014.

As shown in Table 7, in both years, there is a significant difference observed in students' attitude towards physics as an interesting subject, trying things at home and/or telling their families about school science activities, doing mathematical calculations and science excursions. There is also a significant difference in student preference for understanding scientific concepts rather than memorising them in both years.

Students entered in this programme with high attitude towards learning through activities, so there was not a significant difference observed on this item in both years. We also found that in 2013, students had awareness that Einstein's discoveries are important for modern technology, and as a result, no significant difference was observed. While, in 2014, there was a statistically significant difference observed in students' awareness about the importance of Einstein's discoveries after the programme.

Gender Analysis of Both Years for the Attitudinal Questionnaire (Objective 3)

Students' Attitude Towards Activity-Based Learning and Calculations

To investigate students' attitude towards activity-based learning, AQ 2 (I prefer to learn physics through activities), AQ 5 (I think doing activities helps me understand and remember new ideas much better than if it is just from books and lessons) and AQ 9 (I enjoy science excursions and would like to have more of them) were combined. Students' attitude towards doing calculations was assessed through AQ 7 (I like doing calculations). In the analysis of AQ 2, AQ 5 and AQ 9, we combined students 'agree' and 'strongly agree' responses together. Amongst the group of students surveyed, there was a strong preference for activity-based learning as shown in Fig. 3a. There was an overwhelming agreement from both male and female students that they prefer to learn through activities and excursions and that this is not only enjoyable, but they learn more by doing so. However, it is clear from Fig. 3a that the male

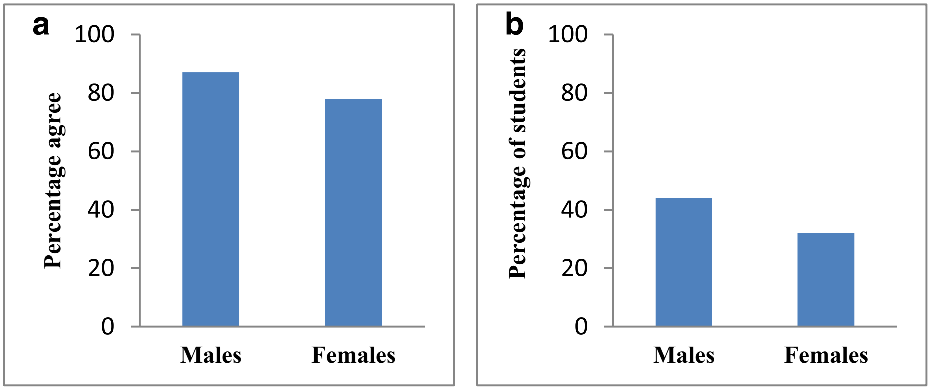

Fig. 3 **a** Students' attitude to learning physics through activities and excursions. **b** Percentage of students who enjoy doing calculations

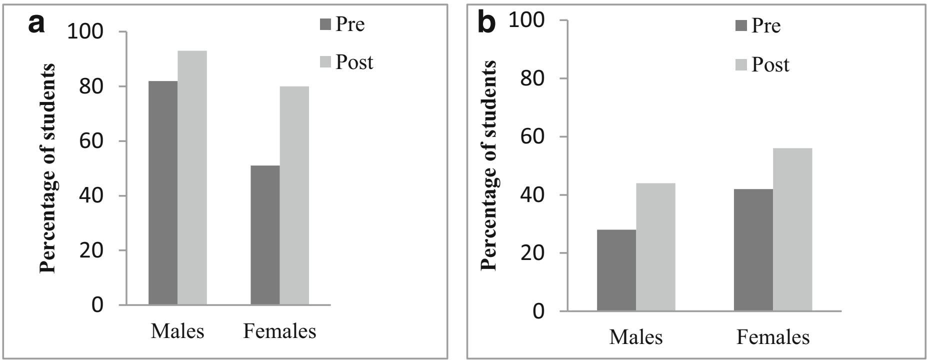

Fig. 4 **a** Percentage of students who think physics is an interesting subject. **b** Percentage of students who enjoy trying things out at home and/or telling family about school science activities

students were more inclined towards learning physics through activities and excursions. It was also noted by the presenter Tejinder Kaur and class teacher Dana Perks that the male students were more enthusiastic to participate in activities in the classroom or outside the classroom and more willing to help in setting up experiments compared to their female counterparts.

Figure 3b shows students' attitudes towards doing mathematical calculations prior to the programme. Most students, and significantly more females than males, do not enjoy calculations and prefer not to be taught calculation-based physics. Only 44% of males and 32% of females showed interest in doing calculations.

Students' Interest in Physics

Student interest in physics was evaluated by AQ 1 (I think physics is an interesting subject) and AQ 4 (I enjoy trying things out at home and/or telling my family about school science activities). The results from these questions are shown in Fig. 4a, b

Figure 4a indicates that initially 80% of males and 50% of females found physics interesting. After the Einstein-First sessions, interest amongst females increased to be almost equal to the initial interest of the males. The degree of interest is explored further by AQ 4 which tried to measure how much their interest in physics translates beyond the classroom. The positive response rate as shown in Fig. 4b is significantly less than that for AQ 1 indicating that maybe the degree of interest is not always high enough to continue outside the classroom. However, there is a significant increase in the interest acknowledged by both males and females after the sessions. The results indicate that the students' interest in physics improved significantly after the Einstein-First sessions.

Relevance of Physics

To measure student awareness of the significance of Einsteinian physics in the modern world, we created AQ 6 (The things that Einstein discovered are important for modern technology). There was an overwhelming agreement with this question with a slight increase evident after the sessions. The result is shown in Fig. 5. This tells us that the students were already aware of the importance of Einsteinian physics before they started the programme. This may indicate that they recognised that the works of Einstein are relevant in understanding modern

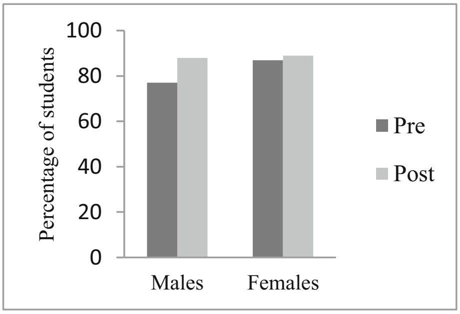

Fig. 5 Most of the students were aware of the importance of Einsteinian physics. This marginally increased through the programme

technologies so as might be expected, there was hardly any change in the students' answers after the programme.

Learning Concepts

Questions AQ 3 (I enjoy learning new concepts and ideas) and AQ 8 (Understanding scientific ideas are more important than memorising facts) evaluated the students' attitudes towards the learning of concepts and ideas rather than information and factual material. The results of these two questions were combined and are shown in Fig. 6.

Figure 6 shows that both males and females already had a positive attitude to learning new concepts. There was an increment observed after the programme. Students prefer to be exposed to concepts and ideas rather than facts and information. There was a significant increase in students' positive response after the sessions.

Students Views About Einsteinian Physics (Objective 3)

We designed a questionnaire to evaluate students' opinion about the Einstein-First Programme. The questions which were assessed are presented in Table 8.

The analysis revealed that 88% of students responded positively to the use of hands-on activities (EQ 1). They agreed that hands-on activities helped to clarify Einsteinian concepts.

There were two lessons in the programme that were based on mathematical calculations. One related to $E = mc^2$, and the other was based on the more mathematically complex gravitational lensing calculations. In response to the EQ 2, 'I like doing calculations on $E = mc^2$', we observed that 57% agreed and 20% disagreed. For the question EQ 3, 'I like doing calculations on gravitational lensing', 34% students agreed and 28% disagreed. Students found

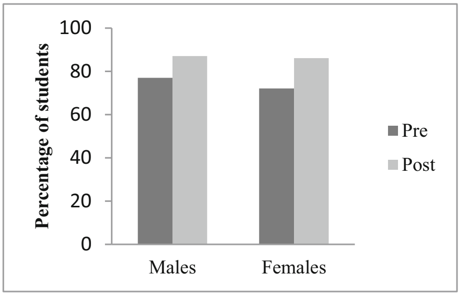

Fig. 6 Both boys and girls enjoyed new ideas and concepts

Table 8 The set of questions asked to the students in the post-test only

Question number (EQ)	Questions asked in the post-test to know students views about Einsteinian physics	Percentage who agree
1.	The hands-on activities were very helpful to you for understanding the concepts.	88%
2.	I like doing calculations on $E = mc^2$.	57%
3.	I like doing calculations on gravitational lensing.	34%
4.	I would like to learn more about Einsteinian physics.	70%
5.	I think Einsteinian physics should be included in the curriculum.	63%

calculations based on energy-mass equivalence easier as compared to gravitational lensing. Most of the students were aware of this famous equation before the programme but did not understand it.

To evaluate the students' eagerness to learn more modern physics, we used EQ 4, 'I would like to learn more about Einsteinian physics'; 70% of students agreed with this while only 7% disagreed. In response to EQ 5, 'I think Einsteinian physics should be included in the curriculum', 63% of students agreed and only 5% of students disagreed while others were unsure.

Delayed Retention Test (Objective 4)

We created another questionnaire to examine whether the Einstein-First programme had a lasting impact on the students involved in the study. The students' retention of Einsteinian physics concepts was tested in two different years. The class attending this programme in 2013 was tested after 1 year. The 2014 class was tested after 3 years. We asked nine questions covering all the concepts taught in the Einsteinian physics programme. The questions are given in Table 9 below.

RQ 1: 2014 and 2017 Results

As shown in the Fig. 7, most of the students were able to recall three key concepts (RQ 1) they had learnt in the Einsteinian physics programme. Their answers included 'space is curved', 'geometry of curved space' and 'light comes as photons'. We noticed that most of the students who did well in the questions related to non-Euclidean geometry in the post-test 1 or 3 years earlier still remembered those concepts. Many students mentioned the concepts they were taught using Nerf guns about the particle nature of light. This demonstrated the power of using models and analogies as a means of conveying physics concepts.

RQ 2: 2014 and 2017 Results

When we asked about any contradictions between the concepts they had learnt in the Einsteinian programme and in year 10 physics, 58% of students mentioned that they found some conflicts between the Einsteinian physics programme and the concepts learnt in year 10, while only 8% of year 12 students found some contradictions after the programme. The reason for the more positive finding for the year 12 students may have been because they had learnt

Table 9 Questions used to test student retention after the Einsteinian programme. This test was conducted twice, one in 2014 for students who attended this programme in 2013 and the other in 2017 for year 9 students who attended this programme in 2014

Retention question (RQ)	Questions asked
1.	List three key concepts you learnt in the Einsteinian physics programme.
2.	Have any concepts you have learnt in physics conflicted with what you learnt in the Einsteinian physics programme? Circle yes or no. If yes, please explain your answer.
3.	The Einsteinian physics programme increased my interest in physics. Please circle your answer. a) Strongly disagree b) Disagree c) Neutral d) Agree e) Strongly agree
4.	Describe how space is related to gravity.
5.	List two properties of space that contradict Euclidean geometry.
6.	Describe an activity or experiment from Einsteinian physics programme that showed light behaving as particles (photons)?
7.	Describe an activity or experiment from Einsteinian physics programme that showed how light can act as a wave?
8.	In physics, scientists can estimate the mass of a galaxy by looking at the light from something far away behind it. What basic idea underpins this?
9.	A typical kettle has a power of about 2000 W. If you fill it with water and switch it on for 1 min, how much will the total mass of the kettle + water have increased? [Hint: Energy = power × time; $E = mc^2$]

some Einsteinian physics concepts in their year 12 physics. The most common contradiction they mentioned was about Newton's explanation of gravity.

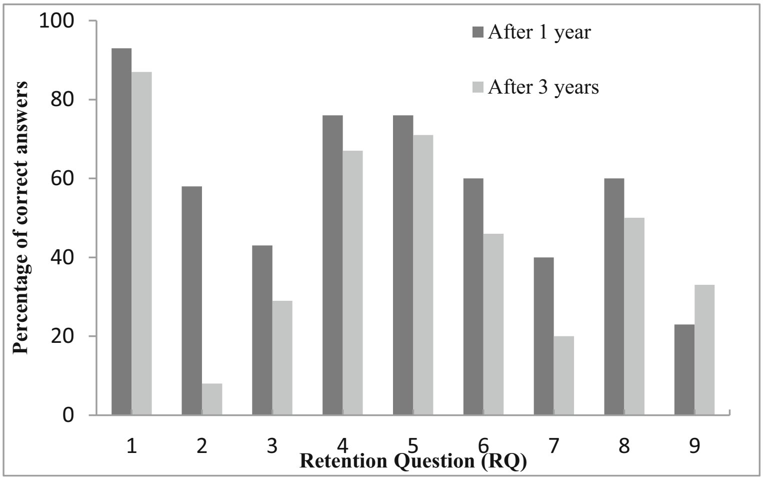

Fig. 7 Students' percentage of correct responses for the delayed retention test after one and three years of the Einsteinian physics programme. The results are displayed according to each question asked in the retention test

RQ 3: 2014 and 2017 Results

Retention question RQ 3 tested whether the Einsteinian physics programme had increased their interest in physics. One year after completing the programme, almost half of the students agreed that the Einsteinian physics programme had made them more interested in physics while only 29% of those who completed the programme 3 years before gave a positive response.

RQ 4 and RQ 5: 2014 and 2017 Results

After 1 year of the programme, 76% of students were able to explain how space is related to gravity (RQ 4) and 67% of students retained this concept after 3 years of the programme. RQ 5 tested their retention about non-Euclidean geometry. A year later, 76% of students remembered the properties of space that contradict Euclidean geometry while 71% recollected it after 3 years.

RQ 6 and RQ 7: 2014 and 2017 Results

A year after the programme, 60% of students could recall the name of the activity they did to understand the particle nature of light; this number decreased to 40% after 3 years since participation in the programme. Furthermore, after 1 year, 40% of the students mentioned the name of the experiment they did to understand the concepts of quantum interference and diffraction, whereas after 3 years, only 20% were able to recall the activity.

RQ 8 and RQ 9: 2014 and 2017 Results

In 2014, 60% of students were able to recall the concept that scientists use to estimate the mass of a galaxy (RQ 8) and half of the students (50%) responded correctly in the 2017 retention test. The programme was based on conceptual understanding and simple mathematics. We asked only one mathematical calculation question (RQ 9). We found that a year after the programme, only 23% of students could solve the numerical problem, but 33% of the students tested after 3 years solved the same problem. We suggest that this improvement was due to their increased maturity, mathematical skills development and overlap with material studied in year 12.

Discussion and Conclusion

The results presented in the previous section provide strong evidence regarding the impact of the Einstein-First enrichment programme on students' improved conceptual understanding, attitudes and retention. We investigated the ability of talented year 9 students to accept and understand the concepts of Einsteinian physics, that is, the degree to which the concepts could be made intelligible to students as this is an important aspect of conceptual change (Posner et al. 1982; Tyson et al. 1997). Before the programme, students had low and variable knowledge and understanding of Einsteinian physics concepts. Afterwards, uniformly high test scores were independent of prior knowledge, demonstrating that the concepts of modern physics, when taught with the help of appropriate activities, appear to become accessible and intelligible to all students. Consistency of results between the two programmes delivered one year apart, plus long-term retention 1 and 3 years later, demonstrates that the learning was meaningful. The measurable improvement of test scores in the second year of the programme with nominally matched classes indicates the benefits of teacher experience and lesson optimisation.

Regarding student attitudes, pre-testing demonstrated very high appreciation of activity-based learning, and recognition of the importance of Einsteinian physics. Clearly, despite having little knowledge of Einsteinian physics (as demonstrated by pre-test knowledge results), students were already aware of its importance. It is not surprising that scores in these aspects changed very little. We have presented evidence that female students showed a larger improvement factor in their attitudes as a result of our Einsteinian physics programme than male students. This overall positive outcome is likely to be due to the interactive methods that we used to introduce the fundamental concepts of Einsteinian physics to the young people, combined with the students' perception of the perceived relevance of Einsteinian physics and a negative perception of the relevance of more conventional physics.

We believe that the gender effect size reported here is sufficiently strong to justify revision of school curricula to include the Einsteinian understanding of the world around us. Given that common sense "is the prejudices acquired by the age of 18" (Wikiquote), we predict that future generations who have learnt Einsteinian science at an early age will accept quantum interference as common sense, and curved space and time dilation as self-evident. Most importantly, if taught by the methods we have demonstrated, we argue that our findings support the assertion that student attitudes to science will improve, and the gender gap in attitude to science will be greatly diminished.

We also investigated student attitudes to the Einsteinian physics programme itself. Students' responses were positive with 70% agreeing that they would like to learn more about Einsteinian physics; only 7% disagreed. The percentage of students who enjoy physics increased significantly, and a greater fraction of students reported that they discussed Einsteinian physics more frequently at home after the program.

The fact that almost 60% of students noted conflicts between Einsteinian physics they learned as part of this programme and the material studied in year 10 (1-year retention test result) highlights the problem of conflicting paradigms emphasised by Stannard (1999) and Feynman (1985).

In conclusion, our research provides substantial evidence that high school physics can be taught within an Einsteinian framework, and that it has positive benefits in improving the intelligibility of Einsteinian concepts and student attitudes to physics. The findings also showed the positive impact that teaching Einsteinian physics has on gender equity by reducing the gap in attitudes towards physics between male and female students. The positive outcomes are likely to be a result of a combination of factors, including the relevance of Einsteinian physics to modern science and technology, the use of analogies and hands-on models to support concepts being visualised and understood by students and the use of engaging group activity learning.

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