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2015 Phys. Educ. 50 436

(http://iopscience.iop.org/0031-9120/50/4/436)

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Using Tracker to understand 'toss up' and free fall motion: a case study

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Abstract
This paper reports the use of Tracker as a computer-based learning tool to support effective learning and teaching of 'toss up' and free fall motion for beginning secondary three (15 year-old) students. The case study involved ($N = 123$) students from express pure physics classes at a mainstream school in Singapore. We used eight multiple-choice questions pre- and post-test to gauge the impact on learning. The experimental group showed learning gains of $d = 0.79 \pm 0.23$ (large effect) for Cohen's d effect size analysis, and gains with a gradient of $<g>_{\text{total}} = 0.42 \pm 0.08$ (medium gain) above the traditional baseline value of $<g>_{\text{non interactive}} = 0.23$ for Hake's normalized gain regression analysis. This applied to all of the teachers and students who participated in this study. Our initial research findings suggest that allowing learners to relate abstract physics concepts to real life through coupling traditional video analysis with video modelling might be an innovative and effective method for teaching and learning about free fall motion.

S Online supplementary data available from stacks.iop.org/PhysED/50/436/mmedia

1. Introduction

Many young students harbour misconceptions (Kavanagh and Sneider 2006) about free fall motion and its scientific representation, for example in graphs displaying displacement versus time (y versus t), velocity versus time (v_y versus t) and acceleration versus time (a_y versus t). When these are not well understood, it is difficult to use them to apply deductive reasoning in different scenarios, such as tossing a ball up with a higher initial speed or on the Moon's surface.

While the use of real-life examples (such as tossing a ball to demonstrate free fall) can be performed by students in class, it is nevertheless challenging for them to translate this world view into x and y coordinates in typical scientific multiple representations (Wong *et al* 2011).

Our study involves the implementation of two 70 min computer laboratory lessons using

  0031-9120/15/040436+7$33.00

the worksheets available at stacks.iop.org/PhysED/50/436/mmedia (free fall–investigate using tracker-student 2.docx), where students fill in the blanks of printouts. There were three pairs of teachers, and each pair taught one class with a total number of students of $N = 123$. A conceptual eight-item multiple-choice questionnaire was used in pre-post-tests to serve as an indication of the learning gains generated after three weeks of wholly traditional and computer-laboratory-based kinematics lessons.

Although not implemented in this study, the video modelling pedagogical approach (Brown 2009) is also recommended for difficult-to-visualize velocity-versus-time graphs comparing two cases; for example, tossing up a ball with (a) greater force (higher initial velocity) on Earth and (b) with the same force on the Moon's surface. The free software tool Tracker[4] can be downloaded from the open source physics website (Christian *et al* 2011) and has been used by a number of *Physics Education* authors (Persson and Hagen 2011, Kinchin 2012, Wee *et al* 2012, Poonyawatpornkul and Wattanakasiwich 2013, Rodrigues and Carvalho 2013).

2. Installation of Tracker

Tracker is a video analysis and modelling tool built on the Open Source Physics (OSP) Java framework. Although it is possible to run it from a 5.6Mb Tracker_487.jar file, we recommend using the installers (see footnote 1), in particular to enable the Xuggle video engine, which can decode most video file formats. Installers for Tracker version 4.87 are available for Windows, Mac OS X and Linux operating systems.

3. Study design

3.1. Purpose of study

The study aims to determine the learning gains from two 75 min computer laboratory lessons (figure 1) that add the Tracker tool and Tracker resource 'bosstossup.trz' (available at stacks.iop.org/PhysED/50/436/mmedia; double click the file in Tracker to launch) to existing typical Singapore school teaching practices for the topic of kinematic free fall. The gains are assessed using Cohen's *d* effect size and Hake's normalized (Hake 1998) gain regression analysis.

[4] www.cabrillo.edu/~dbrown/tracker

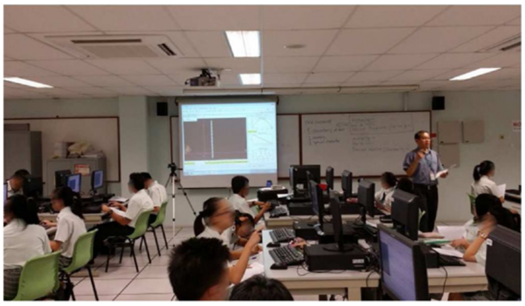

Figure 1. Typical computer laboratory lesson setup, with a teacher guiding approximately 40 students through a hands-on activity that uses Tracker to teach/learn the kinematics of free fall.

Table 1. Class sizes for the instructors of the experimental group. Students were taking ordinary level pure physics.

Teachers	Class	Number of students N
TKK and GCW	3C	41
RT and NSH	3I	38
ACS and SWL	3R	39
Total	3	123

3.2. Methodology

3.2.1. Research design. A case study approach was adopted with the aim of providing a richly descriptive analysis of the impact of using Tracker on student learning in a normal school setting.

3.2.2. Participants. The participants in this study are shown in table 1. In the 2 × 75 min computer laboratory lessons the secondary-three-level (15 year-old) students were divided into classes of ~40 pupils, with a pair of teachers per class.

3.2.3. Lesson plan. The plan was to use these 2 × 75 min computer laboratory lessons to allow students to gain personal experience of the physics of ball 'toss up' motion. The worksheet served as a guide to support the use of Tracker and also to prompt students to predict-observe-explain (Radovanović and Sliško 2013) what they were supposed to understand.

3.2.3.1. Teacher professional development. The six teachers were introduced to Tracker approximately three months before implementation of the lessons. Teacher TKK lead the training sessions with the other secondary three physics teachers in the school as part of the Singapore schools professional learning community team effort, a 2012 initiative from the Singapore Ministry of Education. They designed the worksheet in regular fortnightly meetings and used a Google site[5] for professional development and maintenance of consistent and high-fidelity teaching practices.

3.2.3.2. Laboratory preparation. The computer laboratory technical assistant installed Tracker on the school's computers; one difficulty encountered was the inability to launch Tracker using the Windows|Start|Programs|Tracker|Tracker icon. The solution devised was to create a shortcut directly to the computer's Tracker installed folder: C:\Program Files\Tracker\Tracker.jar. This error was fixed in subsequent releases of Tracker as a result of our feedback.

3.2.3.3. Laboratory activities. The teachers guided the students, aided by a customized worksheet showing the steps necessary to open Tracker and load the video 'tossup.mov' using the teaching staff's computers and laboratory projectors (figure 1). Typically, one teacher showed and explained how to use Tracker, with one or two other teachers around to help with any issues arising from the hands-on activities.

3.3. Data collection instruments

3.3.1. Pre-post-test. An online[6] pre-post-test was constructed, which referenced the activity and worksheets to align the learning tasks with the test items.

3.3.2. Focus group discussions with students. To gather more qualitative evidence regarding the lessons, post-lesson focus group discussions were conducted with a total of nine students from teacher TKK's class divided into three groups. The discussions also provided insights into data that the authors wished to rationalize; for example, the negative pre-post-test results registered for some students, who had answered 4–6 questions correctly out of eight (50–70%) in the pre-test.

3.3.3. Informal discussions/interviews with teachers. The discussions revealed that some of the students and teachers were not comfortable using Tracker, as it was new to them, and that they would require further support to conduct lessons accurately according to the lesson plans. The pairs of teachers served to address this issue, as the partner teacher was able to co-teach and support the lesson.

As the worksheet was being employed in lessons for the first time, some difficulties surfaced while students used it. The newly designed worksheet benefitted from our research, for example through more appropriate scaffolds, such as more closely targeted hints.

3.4. Data collection procedures

At the beginning of the first computer-based lessons, students were told to complete the pre-test in the first 10–15 min after they had navigated to the lesson site.[7] Students were encouraged to complete the pre-test as it would give the teachers an idea of what parts to focus on later in class. Some students managed to discuss their answers, and this may have contributed to some students with 50, 62.5 and 75% correct scores at pre-test later registering lower post-test scores.

After the end of the topic on kinematics, about three weeks after the first lesson, the students were brought back to complete the same items post-test, individually and without discussions.

3.5. Results

Table 2 shows the pre- and post-test results for the eight kinematics questions, tabulated as percentages of the 123 students. The average number of correct scores pre-test was 33% and post-test it was 48%.

3.5.1. Questions 1 to 6. Questions 1, 2 and 3 test students' ability to recall and identify simple y versus t, v_y versus t and a_y versus t graphs, with each registering gains ranging from 16 to 23%.

Question 4 is a common conceptual test item that requires students to understand that the velocity and acceleration at the highest point of the vertical toss-up motion is zero and non-zero, respectively. The change for this was +10%.

Questions 5 and 6 are simple understanding test items that require students to know that when the ball moves upward and downward, the

[5] www.tinyurl.com/evg3phy
[6] https://docs.google.com/forms/d/1zm9NWWC7DWHkO2OYdbf150YyivJFPJeuT5vkO_KFKdI/viewform
[7] www.tinyurl.com/evg3phy

Table 2. Percentage of students (total number of students = 123) who selected (a)–(d) for questions Q(1)–(8). The correct response for each question is italicized. The average percentage of correct answers was 33% pre-test and 48% post-test.

Pre-test								
Q	1	2	3	4	5	6	7	8
(a)	18	34	***39***	46	79	4	27	15
(b)	***55***	29	24	31	***17***	13	27	18
(c)	25	***34***	30	***11***	2	***24***	***40***	26
(d)	2	3	8	12	2	58	***6***	***41***
Post-test								
Q	1	2	3	4	5	6	7	8
(a)	11	22	***57***	51	42	7	23	19
(b)	***71***	20	14	22	***50***	14	28	34
(c)	17	***56***	26	***21***	6	***54***	***44***	16
(d)	1	2	3	6	2	25	4	***31***
Change	**16**	**23**	**19**	**10**	**33**	**30**	**4**	**–10**

gradient of the displacement-time graph is positive and decreasing in magnitude, and negative and increasing in magnitude, respectively. The change for these was higher, at around 30%.

3.5.2. Questions 7 and 8. Questions 7 and 8 are applications test items. In question 7 the v_y versus t graph on Earth is given (green), where the higher initial velocity would result in a parallel but higher v_y intercept line (blue). The change was only +4% for this. For question 8, the v_y versus t graph on Earth is given (green), and here a lower gravitational acceleration would result in a line with the same intercept but a smaller gradient. This time the change was −10%.

3.6. Discussion

3.6.1. Questions 1 to 6. Questions 1 to 6 registered positive gains, which is to be expected. Interestingly, question 4 option (a) also registered a small +5% gain, from 46% to 51%, suggesting that the misconception that an object at the top of its motion suddenly has zero acceleration remains pervasive and that this is a difficult concept to understand correctly; we hope to design better lessons to address this in future.

3.6.2. Question 7 and 8. Question 7 is almost unchanged, with a 4% gain. This is not surprising, as the teachers did not explicate this concept using Tracker's modelling pedagogy (Wee *et al* 2012), which we argue holds great potential for experiential learning and deepening understanding.

Question 8 surprisingly registered a −10% change, which, after analyzing option (b), suggests that students were 'tricked' by 'due to lower mass with higher air resistance', not realizing that it will be a terminal velocity trail when time is large, while the correct answer of (d) is a linear trail suggesting constant acceleration with no drag.

3.7. Results

Based on the scores collected for the pre = 1, post = 2 test made up of eight multiple-choice questions, all three classes ($N_1 = N_2 = 123$) registered positive gains after the incorporation of two hands-on computer-based laboratories with Tracker into a traditional three-week block of lessons on the kinematics of toss up and free fall motion. Classes C (blue), I (red) and R (green) all registered gains (figure 2) and it is worth noting that the total scores (purple) were $\bar{x}_1 \pm s_1 = (2.568 \pm 1.298)$ and $\bar{x}_2 \pm s_2 = (3.839 \pm 1.868)$. This translates to Cohen's d effect size = 0.79 ± 0.23 using equation (1), which can be interpreted as a large effect (Cohen 1977) or practically significant (Wolf 1986):

$$d = \frac{\bar{x}_2 - \bar{x}_1}{\sqrt{\dfrac{(N_1-1)s_1^2 + (N_2-1)s_2^2}{N_1+N_2-2}}}. \qquad (1)$$

Using the normalized gain (Hake 1998) $\langle g \rangle$ in equation (2), where the post-test and pre-test scores are x_2 and x_1, respectively, and 8 is the maximum score for the test, we analyzed the normalized

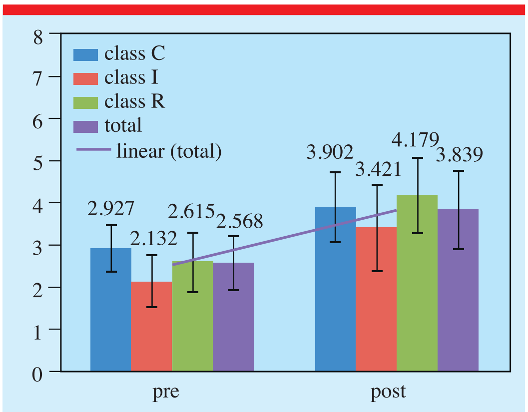

Figure 2. Bar chart of pre-post-test scores of students from class C (blue), I (red), R (green) and the combined total (purple) (left to right) showing total pre-test and post-test scores $C_{pre,\ post}$= (2.927 ± 1.237, 3.902 ± 2.022), $I_{pre,\ post}$ = (2.132 ± 1.104, 3.421 ± 1.648), $R_{pre,\ post}$ = (2.615 ± 1.407, 4.179 ± 1.824) and $TOTAL_{pre,\ post}$ = (2.568 ± 1.298, 3.839 ± 1.868).

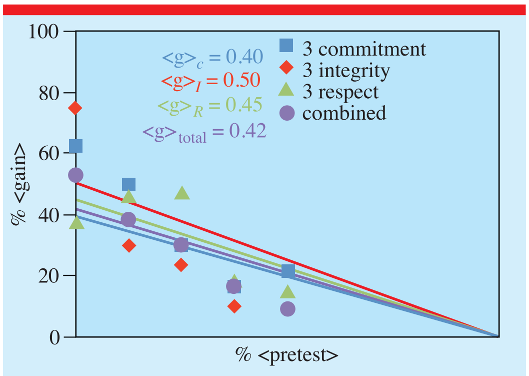

Figure 3. Gain versus pre-test for all three classes. Pre-test scores ranging from 0 marks, 0%, to 4 marks, 50%, are given on the horizontal axis and the gain in percentage is given on the vertical axis. Note that the gains range from 0.40 to 0.50, with $<g>$ total = 0.42 suggesting that the lessons are as effective as most interactive engagement lessons, above the traditional lesson gains of 0.23, as reported in Hake (1998a).

learning gains in percentages across the three classes' pre-test scores as the horizontal axis:

$$<g> = \frac{x_2 - x_1}{8 - x_1}. \qquad (2)$$

We used only the pre-test data equal to and below 50%, as $<g>$ is generally negative for pre-test scores of 62.5% and 75%, and there were no students with 87.5% or 100%. Our interviews with eight students suggested that the negative gains might be attributed to a longer pre-test time of 15 minutes compared to the post-test time of 10 minutes and the benefits of peer discussion the during pre-test.

The general trend was not adversely affected by neglecting scores from 62.5 and 75%, thus we chose scores of 50% and below to simplify presentation. The results from passing through (0%, 0%) linear regression using $<g>$ data in percentage versus pre-test scores (figure 3) suggest that the three classes' normalized gains $<g>$ are near the medium gain classification: $<g>_{C}$ = 0.40 (blue), $<g>_{I}$ = 0.50 (red), $<g>_{R}$ = 0.45 (green) and $<g>_{total}$ = 0.42 (purple) are in a range of gradients well above the traditional normalized gain of $<g>_{traditional}$ = 0.23.

Based on the standardized mean difference, Cohen's d = 0.79 (large effect) and normalized gain $<g>$ = 0.42 (medium gain) analysis, the evidence suggests that the students did learn about kinematics concepts more effectively than they would have with traditional passive, non-interactive lessons.

We recommend use of a design-based research (Juuti and Lavonen 2006) method to continually improve these Tracker-based lessons, as this is the first year that teachers have conducted them, and we believe that there is still much scope for improving their implementation and deepening the learning experience through video modelling (Brown 2012a), not elaborated in this paper.

4. Students' reflections on the Tracker lesson

To give some insights into the conditions and processes seen during the laboratory lessons, the following are some excerpts from the informal interviews with students. Words in square brackets [] have added to improve the readability of the qualitative interviews.

4.1. Tracker supports interactive and real-world physics

'We are able to see the connections between real life [video] and the [scientific] graph[s]. Tracker helps me to confirm the theory [in kinematics] I have learned.'

'The video analysis [Tracker] gives me the opportunity to check the data collected. I realized that in real-life data collection there are random errors, which was shown from the graph plotted.'

'Compared to teachers' explanations on the board, video analysis gives us more opportunity to have a real learning experience, rather than being spoon fed with content. By allowing us to use the video analysis [Tracker], we have been able to see more precisely [the relationship] between the ball and the graph plotted.'

'Perhaps we can have a practical lesson [a performance task] in the curriculum. We would be interested in trying it out ourselves, doing the experiment and recording the videos ourselves.'

4.2. Overcoming initial difficulties using Tracker

'I do not have the experience to load the video and track the video. I would like teachers to use the video Tracker to show us the scenarios in learning, so that we can strike a balance between learning effectively and not spending too much time in setting up the video [tool] Tracker.'

To address this difficulty, teacher TKK has created YouTube video tutorials[8] to help his students.

5. Teachers' reflection

Despite the relative success of the Tracker-based learning, the teachers reflected on the method and made three recommendations for improvement.

5.1. Start using Tracker for easier horizontal kinematics tasks

Start the year with an easier horizontal kinematics task, such as investigating a constant speed object moving on a frictionless track. This will serve to address the cognitive overload (Roth 1999) problem encountered when using Tracker and the relative complexity of the toss up and free fall motion concept for new secondary three students.

5.2. The practice of video modelling, especially for questions 7 and 8

As mentioned before, the teachers were only became aware of the video modelling approach later, and were unable to incorporate this approach across all three classes. Thus, subsequent teaching interventions will include direct instruction from teachers regarding the video modelling activities not explained in this paper.

5.3. Integration of Tracker into the teaching/learning of kinematics, dynamics and work, and energy

We also recognize that for sustained learning gains to be achieved Tracker use should be integrated into the teaching/learning of topics like kinematics, dynamics and work, and energy, so that Tracker's analytical capabilities can be employed seamlessly.

6. Conclusion

This case study involved (N = 123) students from express pure physics classes at a mainstream school in Singapore. We used eight multiple-choice questions pre- and post-test to gauge the impact of our activities on learning. The experimental group showed learning gains of d = 0.79 ± 0.23 (large effect) for Cohen's d effect size analysis, and gains with a gradient of $\langle g \rangle_{total}$ = 0.42 (medium gain) for Hake's normalized gain regression analysis. This applied to all of the six teachers and three classes in the study. The evidence suggests the students learned kinematics concepts more effectively than they would have with traditional passive, non-interactive lessons.

We have made three recommendations to further strengthen learning. (1) Start using Tracker for easier horizontal kinematics tasks to lower cognitive loading for novice students; (b) use the video modelling pedagogical approach (Wee *et al* 2012) to improve learning targeted at questions 7 and 8; and (c) integrate Tracker into the teaching of kinematics, dynamics and work, and energy, to promote sustainable and seamless learning with it.

Acknowledgments

We wish to acknowledge the contributions of D Brown, W Christian, M Belloni, A Cox, F Esquembre, H Gould, B Junkin, A Titus and J Tobochnik to the creation of the Tracker video analysis and modelling tool. This research was made possible thanks to eduLab project

[8] www.youtube.com/user/kimkiatan/videos

NRF2013-EDU001-EL017 ‘Becoming scientists through video analysis’, awarded by the National Research Foundation (NRF), Singapore in collaboration with National Institute of Education (NIE), Singapore and the Ministry of Education (MOE), Singapore.

Received 12 January 2015, in final form 10 March 2015, accepted for publication 31 March 2015
doi:10.1088/0031-9120/50/4/436

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