Encouraging pupil error may promote better understanding of a scientific concept

Michael Allen

Can a science misconception be corrected by using illusions?

Errors, like Straws, upon the surface flow;
He who would search for Pearls must dive below.

(John Dryden, *All for Love*, 1678)

Illusions are rather interesting phenomena. Take for instance the Necker cube (Figure 1), perhaps the most well known of optical illusions. The object is merely a series of lines on flat paper, but the human brain transforms it into a 3-D cube whose structure appears almost real. More about the Necker cube later, but what have illusions to do with teaching science?

A couple of years ago I was supervising a year 10 (ages 14–15) practical lesson on heat insulation. This is a very common secondary school practical with which many readers will be familiar. Cups containing hot water are wrapped in materials such as bubble-wrap, aluminium foil, etc., with the aim of comparing the rates at which the water cools down. Unfortunately, one group of four pupils had misinterpreted the instructions and used cold tap water instead of hot water from the kettle. Their results were fascinating:

Sir, I think bubble wrap is the best because it went up the most – by 5 °C. (Jon)

Obviously, a material such as bubble-wrap would be good at keeping the heat in hot water, but surely it was impossible for it to actively warm cold water? I asked Jon to go away and repeat the experiment:

It's only gone up by 2 °C this time Sir. (Jon)

Perplexed again, I carried out the experiment myself and invited Jon and his group to watch. This time, we all witnessed that there was no change in temperature. What had happened the first two times for Jon to report something that was scientifically impossible? The answer lay, I later came to realise, in Jon's expectations before the experiment. Perhaps he had noticed that if he covered his hand with some loose bubble-wrap it felt warm, and transferred this knowledge to the cold-water experiment: he expected the water to get warmer

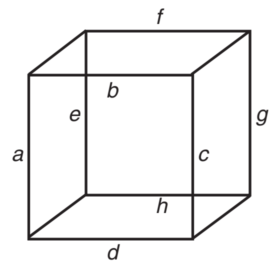

Figure 1 The Necker cube – a common example of how we can influence what we see.

ABSTRACT
An experiment is described where learners carried out activities designed to produce scientific illusions. These illusions depended upon the learners' prior conceptions, and the tasks involved observing two objects of differing mass fall from the same height. Significant learning gains occurred within the experimental group, and it is proposed that a reason for this was the elicitation of learners' emotions. The findings are discussed with reference to the conceptual change movement and to the importance of feeling emotion during a learning experience.

too and he observed just that, even though this did not really happen. As a direct result of using his prior knowledge, Jon had experienced a kind of scientific illusion. I will never forget the looks of amazement (and slight embarrassment) on the faces of the group when they realised their error. The emotional nature of the experience had touched quite deeply, and was frequently referred to in class for many weeks afterwards. I remember thinking to myself if only all my lessons could be this memorable.

Introduction

There is a plethora of literature reporting how the past experience of learners can influence the acquisition of new ideas, e.g. '*prior knowledge plays an essential role in subsequent learning*' (Tsai, 1999: 83). Much of this science-related knowledge has been acquired informally outside the classroom, and it is sometimes faulty. Such scientifically incorrect knowledge has been termed 'misconception', and since the late 1970s much of the research into science education has focused on the nature of these flawed concepts.

My research aimed to help correct a common misconception about falling bodies:

> *If two objects with the same shape but different mass are dropped from the same height, which will hit the ground first? (Figure 2).*

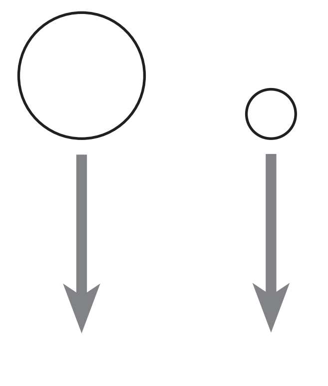

Figure 2 Which ball will land first?

Galileo argued and proved that if air resistance can be negated, both objects will hit the ground at exactly the same time. However, if a group of learners are asked this question, a significant proportion will state that the heavier object will land first. Gunstone (1994) found that a majority (10 out of 16) of student teachers predicted and *saw* a shot put hit the ground before a rubber ball, when they were released simultaneously. A bright student predicted that an aluminium cube would strike the floor first if dropped at the same time as a plastic cube of equal size. After a demonstration, he swore that the aluminium cube had indeed landed first, even when most of the class reported seeing them land at the same time (Driver, Guesne and Tiberghien, 1985). My own piloting with pupils aged 11–16 years revealed that typically 70–100 per cent of those tested give a similar scientifically incorrect response (hereafter referred to as the heavy/light misconception).

The research involved 11–12 year-old pupils in a mixed-ability secondary school in the South-East of England completing a *practical* lesson designed to overcome this misconception. Previous attempts to repair misconceptions have usually involved the learners completing written work of some kind (e.g. Tsai, 1999); a practical approach is unusual but not unheard of (e.g. Shepardson and Moje, 1999).

The practical lesson required the participants to predict which object would land first, and then to physically test their hypotheses. Key design features built into the lesson made it likely that the learners would:

- at the start collect data that were ambiguous;
- near the end collect data that were more conclusive.

The intention was that by (at first) making it difficult to tell which ball landed first, the pupils would be influenced by personal biases and be inclined to report results that agreed with their predictions, that is, they would see what they expected (wished?) to see. As the experiment progresses, each subsequent task becomes easier to interpret, making it increasingly more difficult to ignore the 'correct' answer. By the end, with the help of a final, powerful teacher demonstration, a significant number of pupils should be observing that the heavy and light balls land together.

All manner of objects were considered during piloting including ball bearings, ping-pong, golf, hockey and cricket balls, but it was found marbles were the best. We made sure that they would give the correct result by dropping heavy and light marbles down a three-storey stairwell – they were repeatedly seen to land together.

Methodology

We carried out a classic pre-/post-test educational experiment, using an experimental group and a control group. The two groups were randomly selected from a sample of 56 11–12 year-old pupils. The groups were matched with respect to ability. On the day of the experiment, there were 27 pupils in the experimental group and 26 in the control group. The experimental group attended a single practical lesson which involved dropping a heavy and a light marble. It was designed firstly to identify pupils having the heavy/light misconception, and then to assist conceptual change to the scientifically correct view (Box 1). The control group attended a single practical lesson with gravity as its theme, where pupils took part in a circus of experiments, also involving a marble drop along with three other simple and related activities.

The experimental and control lessons were taught simultaneously but separately by different members of staff, with both lessons starting with a written three-question pre-test to further ascertain equality between the groups (see Box 2). Only one of these questions (Q3, dubbed the critical question) tested the heavy/light misconception.

The three activities carried out by the experimental group were:

Box 1 Experimental group lesson

Pre-test
Learners make predictions
Activity 1
Activity 2
Activity 3
Learners look at their data and make a final choice
Answer is revealed by reading a text that refutes the misconception
Correct concept is reinforced by teacher demonstration using light gates and sense and control

- Activity 1: Pupils dropped their heavy and light marbles at the same time, and looked carefully to see which one landed first.
- Activity 2: Pupils dropped the marbles one at a time and timed their descent using a stopwatch. A shorter time means a quicker fall.
- Activity 3: Pupils repeated activity 1 but using a simple piece of apparatus (a card 'tunnel' – see Figure 3) that allowed marbles to be dropped (a)

Box 2 The pre-test

Think about each of the following statements and tick only *one* of the four boxes under each question

Q1 A trolley freewheels down a slope.

- Adding more weight will make the trolley go *further*. ❑
- Adding more weight will make the trolley go *faster*. ❑
- Adding more weight will have no effect ❑
- You do not know what effects adding more weight will have. ❑

Q2 A skydiver jumps from an aeroplane.

- She will fall faster if she spreads her arms and legs as far out as possible. ❑
- She will fall faster if she curls into a ball. ❑
- She will fall faster if she takes up a head-down, dive position. ❑
- She will fall faster if she opens her parachute. ❑

Q3 Signor Galileo decides to drop two cannonballs from the top of a tall building at exactly the same time. One of the balls is twice as heavy as the other.

- He finds that both balls hit the ground at the same time. ❑
- He finds that the heavier ball lands first. ❑
- He finds that the lighter ball lands first. ❑
- You do not know which ball will land first. ❑

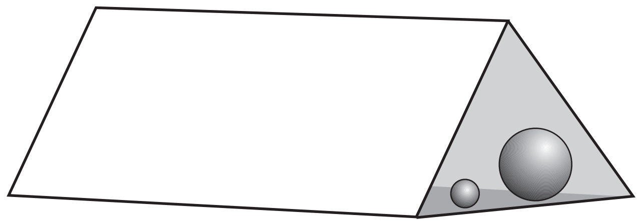

Figure 3 The 'card tunnel'. Cut a 15 cm square from card and fold as shown to create an open-ended Toblerone-shaped tube. Clamp the tunnel about 30 cm from the bench top. Line both marbles up, side by side and release them simultaneously.

from the same height and (b) at the same time, so making a fairer test. Pupils were asked to listen to the sound as the marbles landed – a single bang meant they must be landing at the same time.

It has been demonstrated that learning may be improved by *reading* about the correct conception and so we revealed the answer by using a refuting text (Box 3), as did Hynd, Alvermann and Qian (1997).

A post-test was carried out 24 hours later, consisting of the pre-test plus three new questions including a second critical question (Q1) – see Box 4. Finally, a delayed post-test was carried out six weeks after the experiment, which was a repeat of the previous post-test.

Results

The percentages of pupils giving correct answers to the critical questions in the three tests are shown in Tables 1 and 2. Question 3 (pre-test) was asked using a familiar context, and in both post-tests tested how well each student remembered the correct answer to the problem (Table 1). Note that the pre-test questions were presented in all three tests, the pre-, post- and delayed post-tests. Question 1 (post-test) was set in an unfamiliar context, and tested how each learner could carry forward their understanding to a new situation (Table 2).

Box 3 Example of refuting text

'Galileo wanted to disprove Aristotle's ideas, which had been used for centuries. He predicted that gravity would affect all falling objects in the same way. To try out his ideas, he dropped metal weights from a tower, probably in Pisa, Italy. He found that, when different masses were dropped at the same time, they hit the ground together. He realised that light things (like feathers) only fall slowly because they are more affected by air resistance.'

(Pople and Denley, 1991: 79)

Conclusions

Using chi-squared analysis it was found that both the experimental and the control group demonstrated significant improvements in their understanding of this particular concept, 24 hours after the lesson (with respect to Q1, for the experimental group $\alpha = <0.001$ and for the control group $\alpha = <0.005$). Six weeks later, this was still the case for the experimental group ($\alpha = <0.001$) but not for the control group, whose learning gains ceased to be statistically significant ($\alpha = <0.2$). These results suggest that practical activities can be useful in correcting this stable misconception. However, the experimental group demonstrated far higher improvements than the control group after the lesson (with respect to Q1, after 24 hours for the experimental group $\alpha = <0.005$ and after 6 weeks $\alpha = <0.05$). Using the pre-test results it was proved that the groups were statistically equivalent with respect to the initial frequency of the misconception ($\alpha = 0.25$).

Discussion

Illusions

My dictionary defines 'illusion' as '*an unreal or misleading image or appearance*'. Returning to the Necker cube (Figure 1), not only can one visualise a 3-D cube but also flip its orientation. You may first imagine the face **abcd** to be nearest to you but, if you

Box 4 The post-test

Think about each of the following statements and tick only *one* of the four boxes under each question.

Two men bungee jump from a crane. One of the men weights 10 stone and the other weighs 20 stone.

Q1 Will the men fall at the same speed?

- Both men will fall at the same speed. ❑
- The lighter man will fall faster. ❑
- The heavier man will fall faster. ❑
- You do not know which man will fall faster. ❑

Q2 Which man will stretch the bungee elastic the most?

- The 10 stone man will stretch the bungee elastic the most. ❑
- The 20 stone man will stretch the bungee elastic the most. ❑
- Both men will stretch the bungee elastic equally. ❑
- You do not know which man will stretch the bungee elastic the most. ❑

Q3 Which man will rebound back up the highest?

- The heavier man will rebound the highest. ❑
- The lighter man will rebound the highest. ❑
- Both men will rebound to the same height. ❑
- You do not know who will rebound the highest. ❑

Table 1 Results for pre-test Q3.

	Correct answers (%)		
	Pre-test	*Post-test*	*Delayed post-test*
Experimental group (*N* = 27)	0	77	67
Control group (*N* = 26)	11	31	33

Table 2 Results for post-test Q1.

	Correct answers (%)	
	Post-test	*Delayed post-test*
Experimental group (*N* = 27)	62	51
Control group (*N* = 26)	15	23

concentrate, the opposite face **efgh** appears to ‘jump out’ and be closer. This illustrates an interesting feature of human perception: the fact that we do not merely see what is there, but can actually change what we see. This model of constructive perception derives from the top-down theories of researchers such as Richard Gregory and the Gestalt psychologists (Gordon, 1989).

The idea that the mind does *not* see reality in a pure way, as a camera takes a photograph, but changes the reality first by mental processing is the stuff of relativist philosophy. The view that we do not see what is actually out there, but only what our mind allows us to see may go against common-sense gut feelings, but there is ample evidence from psychology experiments that suggests we do just that. Studies by

Elizabeth Loftus in the 1970s (Loftus, 1980) showed that road traffic accident witnesses often recalled details of the event that did not actually occur; many were influenced by prior expectations, e.g. sports cars travelling faster than they actually were. Children who are shown abstract drawings similar to ink blobs just before lunch have a tendency to report seeing food among the random shapes (Sanford, 1936).

Using illusions to aid learning

This very human tendency of allowing what we expect to happen to have some influence on what we actually see happening can be demonstrated by learners in a school science laboratory. The learners in the experimental group were actively encouraged to make such mistakes; eventually bringing to their attention the fact they have erred, elicits an emotional response that may assist conceptual change and later recall. There has been a recent upsurge in interest in emotion-mediated learning in *School Science Review* articles (Hadzigeorgiou, 1999; Alsop, 2001) and the relevance of affect to successful education is well established (Goleman, 1996).

The lesson given to the experimental group followed a constructivist tradition that is well described in the educational literature. Data are presented that may be contrary to what is presently believed by a pupil, and 'conceptual conflict' takes place that will hopefully result in the correct concept displacing the poor one. This approach is not new and harks back to Piaget's principles of accommodation and assimilation, where fresh mental input is both accepted by and changes existing schemata (Hayes and Orrell, 1993). The lesson design allowed pupils to try out their ideas experimentally in a relatively loose fashion (in contrast to traditional classroom techniques that may tell the answer didactically), so encouraging them to discover the answer themselves in a practical way. The heavy/light misconception has been shown to be extremely resistant to teaching and, as previously mentioned, has been demonstrated in the academically successful (student teachers); however, success in repairing this and other scientific misinterpretations may be optimised by the methods advocated by this study:

> *It is essential that the children change their ideas only as a result of what they find themselves, not by merely accepting ideas which they are told are better.* (Nuffield Primary Science SPACE Project, 1995: 5).

It was interesting to follow the thinking of the pupils as they carried out the activities. Prior to the lesson, 20 out of 27 of the experimental group verbally predicted that the heavy ball would land first. During the first two activities, 12 of these 20 recorded that the heavy ball had indeed fallen faster, as did 2 pupils who had predicted the light ball would win. In all, 19 of the 27 pupils observed what they predicted (random results would generate only 9 pupils doing this). These activities were designed to be difficult to observe and give ambiguous results, and so this clearly shows the influence expectation can have on observation in the presence of doubtful data. This is a very human quality: if we are unsure about a conclusion we may be tempted to go for the answer with which we are most comfortable, whether the context is a scientific experiment or unkind rumours about a friend. It was, however, encouraging that, after the final phase of the experiment, activity 3, the refutational text and teacher demo (designed to offer very conclusive data supporting the scientific view), reasoning had overcome the pupils' previous allegiance to the misconception and none of the experimental group reported that the heavy ball landed first.

The main aim of the experimental lesson was not merely to expose the pupils to practical activities that gave a 'correct' answer, but also to engage them at an emotional level. We think that we were successful on this count, because the lesson plays as a kind of game, with different pupils taking sides, supporting one or the other of the possible outcomes. Some will be dogged and stick with their predictions even in the face of quite irrefutable data, while others chop and change according to whatever their friends across the room are saying. The pupils appeared to enjoy this freedom to think and have their say. When the correct, scientific answer was revealed there were (muted) cheers from the 'winners' and slightly embarrassed looks from some of the 'losers'. The core thesis of this approach to practical work is that causing learners to experience such emotions as pride, excitement, tension (as they await the answer), surprise and even the shame of failure, is likely to result in more effective learning. If one reflects on one's own life, is it not the emotionally charged episodes such as falling in love, being involved in a fight, exam success or disappointment that we remember most vividly?

Victims of illusions or cheats?

A limitation of this experiment is the fact that we did not examine the reason why a pupil made a particular observation error. Pupils record incorrect results for reasons other than illusion, such as misreading apparatus, forgetfulness between observing and writing the result down, and just plain cheating. The experiment is part of a larger and ongoing study and it is planned to investigate these issues in detail later using a qualitative methodology. The study is looking at around 30 fruitful areas of school science where misconceptions occur and illusions might be common, including whether a balloon has weight, differentiating between the colours of pH 7 and pH 9, conduction of heat through metal rods of different diameter, dropping a 'bomb' from a moving 'aircraft' and the change in mass of a solution after dissolving. To create your own illusion experiments to try with classes, all you need is a misconception and a method that produces inconclusive results! After this study is complete, it is hoped the experiments will be published in a form that teachers can use and incorporate into their repertoire, and with reference to the QCA (Qualifications and Curriculum Authority) schemes of work.

Summary

The pupils in the experimental group were encouraged, by the use of activities that supplied ambiguous data, to make observation-related errors in the hope that this would elicit emotional responses and aid learning. Pupils in the control group carried out marble drop activities and probably made similar errors that went unchallenged and so led to the reinforcement of their mainly incorrect prior beliefs. Learners in the experimental group had undergone a more intensive experience, designed to make the event more memorable by activating their emotions. They had been forced to face any previously held concepts and to attempt to justify them; if these ideas were incorrect they would wither under the fire of the irrefutable practical scrutiny.

> *We often discover what will do, by finding out what will not do; and probably he who never made a mistake never made a discovery.*
> (Samuel Smiles, *Self-help,* 1859).

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Michael Allen is head of science at a middle school in Windsor, Berkshire. He is completing a PhD (part-time) at Brunel University. E-mail: Michael.allen@brunel.ac.uk

Notes and news

Funding for your projects?

Do you have an idea which needs funding to make it happen? For amounts up to £400 the PPARC/Institute of Physics School Grants Scheme may be the answer. If you need more (up to £15 000) then you can try the PPARC Small Awards Scheme.

The PPARC/IoP School Grants Scheme

This new scheme aims to provide schools with grants of up to £400 for small-scale projects or events linked to the teaching or promotion of physics. Projects linked to astronomy, space and particle physics are particularly encouraged.

The grant could be used to support a range of projects, for example:

- running a school/college-based science week activity
- purchasing materials/resources outside of the normal department resources
- organising a visit to or from a working physicist

The scheme is open to all UK educational institutions (schools and colleges) catering for pupils/students in the age range 5–18.

For details of the scheme, and an application form, see: http://teachingphysics.iop.org/teacher_support/schoolgrants/index.html

The PPARC Small Awards Scheme

The scheme can provide between £500 and £15 000 for projects relevant to publicising or teaching the PPARC-funded science areas – broadly astronomy, space and particle physics. Applications from schools are particularly encouraged. Recent funded projects in schools range from primary school 'space days' to the production of resources to support the teaching of astronomy.

Application materials and examples of previous winners can be found at: http://www.pparc.ac.uk/Rs/Fs/Pu/funds.asp

For further information, contact: Science & Society, PPARC, Polaris House, North Star Avenue, Swindon SN2 1SZ.
Telephone: 01793 442098
Fax: 01793 442002
E-mail: Malcolm.Booy@PPARC.AC.UK

Salters' National Awards for Science Technicians

The Salters' Institute, in collaboration with the ASE, the IOB, the IoP, The Royal Society and the RSC, established the first National Awards for Science Technicians.

In 2005 The Salters' Institute is entering the fourth year of the Awards.The aim of the Awards is to acknowledge publicly the immense contribution that science technicians make to the well-being and success of schools and colleges and, in particular, science departments. We hope very much that the Awards will heighten awareness of the importance of science technicians to education in this country. The closing date for nominations is 1 May 2005.

Further information and a nomination form can be obtained from: institute@salters.co.uk or on www.saltersinstitute.co.uk.

Physics Update course

An *Update course* for practising teachers of physics is to be held at Royal Holloway, University of London, from Friday 8 to Sunday 10 April. The course consists of a series of talks and workshops, and participants will hear about recent developments in physics and its applications, try new practical techniques and find out about developments in physics education.

Information: Leila Solomon,Institute of Physics, e-mail: leila.solomon@iop.org

Summer school for teachers in Sweden

The European Association for Astronomy Education is holding its ninth summer school for primary and secondary teachers from 8 to 13 August 2005 in Skara, Sweden. Around sixty European teachers will attend general lectures, working groups, workshops and observational sessions in astronomy. The event is not aimed at experts and the presentations will be in English.

Approximate cost of registration and accommodation is 750 Euros. British Council support may be available. Closing date for registration is 30 April.

Contact: Alan_C_Pickwick@btinternet.com
Telephone: 0161 973 6796