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Can the principles of cognitive acceleration be used to improve numerical reasoning in science?

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ABSTRACT This study investigates whether the Cognitive Acceleration through Science Education (CASE) scheme could be used to meet the demands of the Literacy and Numeracy Framework (LNF). The LNF is part of the Welsh Government's improvement strategy in response to perceived poor performance in the Programme for International Student Assessment (PISA) surveys by students in Wales. It reviews some research evidence for the approach and studies current use within North Wales. Finally, it suggests a way in which these principles could begin to be adapted within science lessons to meet the requirements of the LNF.

Since devolution in 1999, education in Wales has been the responsibility of the Welsh Government. The structure of the education system has remained similar to that in England, although education policies have diverged noticeably. During recent years, there has been increasing concern expressed in Wales that the level of performance of students in numeracy (and literacy) has been declining (Andrews, 2011; Dauncey, 2013). The main evidence used to support this assertion is Wales's performance in the Organisation for Economic Co-operation and Development (OECD) Programme for International Student Assessment (PISA) surveys carried out in 2006, 2009, 2012 (National Assembly for Wales, 2013) and 2015 (Jerrim and Shure, 2016). Despite concerns about the validity of the international comparisons, it remains clear that, when the scores from all four rounds of PISA tests in the UK are analysed, Wales is the poorest performer. Although the education systems in each country do differ to some extent, the fact that Wales is performing less well than countries that are educationally and culturally very similar is a cause for concern.

A major part of the response by the Welsh Government to these concerns has been the introduction of the National Literacy and Numeracy Framework (LNF) in September 2013 with a new annual system of literacy tests (in English and/or Welsh) and procedural numeracy and numerical reasoning tests following from September 2014 (Welsh Government, 2013).

The numeracy framework is separated into four strands; each of these strands is split into a number of elements, as shown in Box 1.

This article has two main aims. The first is to identify opportunities to apply numeracy skills, particularly numerical reasoning, in

BOX 1 Elements of the four strands of the numeracy framework of the LNF (Welsh Government, 2013)

Developing numerical reasoning:
- identify processes and connections;
- represent and communicate;
- review.

Using number skills:
- use number facts and relationships;
- fractions, decimals, percentages and ratio;
- calculate using mental and written methods;
- estimate and check;
- manage money.

Using measuring skills:
- length, weight/mass, capacity;
- time;
- temperature;
- area and volume;
- angle and position.

Using data skills:
- collect and record data;
- present and analyse data;
- interpret results.

scientific contexts. The second is to identify pedagogical approaches that allow these skills to be developed effectively.

Numeracy in science

The numeracy skills of students are important in the teaching, learning and understanding of science (Lenton and Stevens, 1999; Ward-Penny, 2011). In the current version of the National Curriculum for Wales, the only numeracy skills that are specifically assessed in science at key stage 3 (age 11–14) relate to data collection and handling. It is, however, suggested that science can contribute towards the teaching of a broader range of numeracy skills. The education and skills inspectorate for Wales, Estyn (2012), found that science departments were providing good opportunities to extend students' numeracy skills as these skills arise as an inherent aspect of the subject. However, Estyn (2013a, 2013b) criticised the range of numeracy skills taught within science lessons, stating that students have a secure understanding of data gathering and handling skills but that there is less evidence of students working on number skills and numerical reasoning.

As students progress to key stage 4 (age 14–16), it can be argued that the 'Developing numerical reasoning' and 'Using number skills' strands become more important, particularly in physics where an ability to interpret and manipulate formulae becomes an important foundation on which to build a deeper understanding of the subject. GCSE physics, the national examination taken at age 16, also makes extensive mathematical demands on all candidates including the use of number skills, data handling and interpretation. Higher tier candidates are also expected to use more complex mathematical content, such as algebra and standard form (Welsh Joint Education Committee, 2015). As it is clear that science lessons can provide a wide variety of contexts in which to teach numeracy skills, the question arises as to how these skills can be taught effectively.

Estyn (2012) cites Cognitive Acceleration in Science Education (CASE), also known as Thinking Science (Adey, Shayer and Yates, 2001), as an example of good practice in teaching students higher order numeracy techniques, as long as it is used well. Informal discussions with science teachers in local schools also suggested that CASE still has some influence over teaching methodology, even if it was not being used currently as a stand-alone course.

Cognitive Acceleration in Science Education (CASE)

Theoretical background and content

CASE is based on the ideas of Piaget and Vygotsky. A set of three principles is intended to help students progress towards higher order thinking skills (Adey, 1999):

- cognitive conflict;
- social construction;
- metacognition.

The principal aim is to encourage the students to move from concrete operational thinking, which allows you to describe a situation, to more abstract, or formal operational, thinking, allowing you to explain a situation. The ability to think abstractly is a key part of learning science. There are five central themes in CASE (Adey, 1999):

1. **concrete preparation**, where the teacher introduces the activity, linking it to work already done;
2. **cognitive conflict**, where the students' preconceptions are challenged, for example, with an unexpected result;
3. **construction**, where students discuss the result in small groups or as a whole class;
4. **metacognition**, where the students think and talk about their thinking;
5. **bridging**, where the new concepts are linked to other contexts.

Discussion between students is a major part of the lesson and is a key factor in raising achievement. This is also suggested to be an effective approach by other studies such as Lenton, Stevens and Iles (2000) and the epiSTEMe project (Mercer, Dawes, Wegerif and Sams, 2004; Ruthven *et al*., 2011).

The CASE materials cover the following concepts (Adey *et al*., 2001):

- variables;
- ratio and proportionality;
- probability and correlation;
- compensation and equilibrium;
- formal models;
- classification;
- compound variables.

These are concepts that would be considered to be part of numeracy, and as such a secure grasp of these concepts in science lessons could be hoped to extend into other subject areas.

Table 1 A comparison of the early part of the Thinking Science course with the numeracy framework of the LNF; adapted from Adey, Shayer and Yates (2001) and Welsh Government (2013)

Numeracy framework of the LNF		CASE lesson(s) covering this strand (number refers to lesson in the Thinking Science course)
Strand	**Element**	
Developing numerical reasoning	• Identify processes and connections • Represent and communicate • Review	1 What varies? 2 Two variables 3 What sort of relationship? 4 The 'fair' test 5 Roller ball
Using measuring skills	• Length, weight/mass, capacity	2 Two variables 3 What sort of relationship? 4 The 'fair' test 5 Roller ball (fair testing, kinetic and potential energies)
Using data skills	• Collect and record data	2 Two variables 3 What sort of relationship? 4 The 'fair' test 5 Roller ball
	• Present and analyse data	3 What sort of relationship? 5 Roller ball
	• Interpret results	1 What varies? 2 Two variables 3 What sort of relationship? 4 The 'fair' test 5 Roller ball

Table 1 maps the coverage of elements of the numeracy framework of the LNF in the first five lessons of the Thinking Science course. It can be seen that that a broad range of numeracy strands and elements are covered within this small number of lessons.

Evidence of the effectiveness of the CASE approach

It is claimed that the CASE approach leads not only to improved results in science at both key stage 3 and GCSE, but also to similarly improved results in mathematics (Shayer, 1999; McGuinness, 1999). Shayer (1999) found that schools that implemented the CASE lessons had a significantly higher percentage of students reaching level 6+ when compared with the national average, and their science GCSE grades were 1 grade higher on average. However, Jones and Gott (1998) suggest that the results attributed to CASE are not so conclusive. Their study in five schools showed improvements in attainment of about half of a National Curriculum level. They also reported that many teachers had found the language developed in CASE lessons to be helpful during their usual lessons on data collection and handling. They agree that many elements of the CASE approach are of value in encouraging students to think about their thinking and that it should form the basis of much science teaching. They did, however, state that they found '*an almost universal feeling that it is suited for the most able children only*' (p. 761). Shayer (1999) stated that the evidence does not support this statement but he does concede that the course was not designed for the least able learners. Jones and Gott (1998) suggest that the CASE approach should be embedded as part of the day-to-day content of the science curriculum rather than as the stand-alone approach advocated by Adey *et al*. (2001).

Current use of CASE in Conwy County, North Wales

As there seems to be evidence in favour of teaching techniques based on the use of metacognition, it was decided to conduct more formal discussions with colleagues about their use of metacognitive learning activities. The intention was to find out whether or how metacognitive approaches were being used, or

Table 2 Semi-structured interview questions related to numeracy strategies

Possible question	Possible follow-up questions	Probes/prompts
Does your department have a common approach to numeracy?	Are there any specific schemes or strategies used in your department?	Suggest names of schemes, e.g. CASE, epiSTEMe
Do your students encounter difficulties whilst carrying out numerical work?	What sort of difficulties? What strategies do you employ to help them?	List of examples of topics; calculations, graphs, etc. . . .
How confident do you feel in tackling numeracy difficulties amongst your students?	Do you feel that you are aware of common misconceptions that students hold?	List of these

what the perceived barriers to its use were, with a view to designing a programme to further develop students' numerical reasoning skills within science.

A semi-structured interview schedule was designed; the questions are given in Table 2. The flexibility of the design allowed the order in which the questions were asked to be modified to suit a particular situation, and additional questions were used to follow up any interesting responses.

Four interviews were conducted: two in one school and one in each of the two other schools. All three schools were suburban, mixed and comprehensive, with a student age range of 11–18; one had fewer than 1500 students, one had about 1500 and the other had more than 1500. The characteristics of the interviewees are described in Table 3.

Table 3 Characteristics of the interviewees in the sample

Interviewee 1	Chemistry teacher, studying for a masters in educational practice
Interviewee 2	Physics teacher, Assistant Head of Science Faculty, and key stage 4/ GCSE coordinator
Interviewee 3	Head of Biology, whole-school numeracy coordinator
Interviewee 4	Chemistry teacher, Deputy Head of Science Faculty, and key stage 3 coordinator

All three schools where interviews were conducted had some experience of using the CASE scheme, even if they did not use it currently. Interviewee 3 stated that their school had run the CASE scheme in the past but that '*pretty much all of it has been taken out now*'. The reason stated was that this was because the students struggled with it: '*It was aimed at the middle to high kids, and the lower end were lost*'. Interviewee 4 expressed some similar concerns regarding the use of CASE, suggesting that you need to pick your groups carefully. They also stated that students at the lower end of the ability range (and with additional learning needs) were unable to access the materials and that '*if you've got a group that are generally very, very low ability, then I don't think it works terribly well*'. Interviewee 4 went on to note that, as the CASE approach encourages students to discuss their ideas, they wouldn't get the opportunity to '*bounce ideas off each other in the way that CASE encourages them to do*'. However they, did suggest that if CASE was used with mixed ability groups consisting of higher and middle ability students, then the '*middle ability students gain a lot of confidence when discussing their ideas with other students*'. The school continues to use CASE, although not always as a '*stand-alone'* scheme, tending to '*dip into*' specific lessons that they have found to be successful and that the students enjoy doing. In general, these views of the value of the CASE scheme for higher and middle ability students seem to echo the findings of Jones and Gott (1998).

It was also decided to conduct a trial (in the lead author's school) into the impact of the CASE scheme on the students' scores in the national numeracy tests. Students sit nationally set tests in numerical reasoning in years 2–9 (ages 6–14). The results are given as an age-standardised score, with the range 85–115 being the 'expected' score. Students' test scores in year 6 (age 10–11, the end of primary school) are available to the secondary school. The first five lessons of the CASE scheme

were run over 10 weeks with two year 7 (age 11–12) classes. The two classes were randomly chosen by drawing names out of a hat, with the other six classes in the cohort being the control group. The scores at the end of year 7 could be compared with the year 6 scores. This would allow the progress of the students in numeracy to be compared, and an evaluation made as to whether the scheme has had an effect on their numeracy skills.

Table 4 shows that the differences between the results were too small to be regarded as significant; any differences could be due to chance. Apart from the small size of the sample there were other factors that could affect the validity of the results. One of the classes chosen for the intervention was a single-sex group, which skewed the gender balance of the two groups. There were also frequent class changes during the course of the year, which reduced the number of students in the intervention group over the year, compared with the initial size of the group.

After the trial lessons, an informal group discussion was conducted with six students from the intervention group. They stated that they had enjoyed the independence that the style of the lessons gave them, along with working in groups of students they wouldn't normally work with. Five of the students found the lessons more engaging because the teacher had led their thought process with careful questioning, so they felt that they had got to the answer themselves. This gave them a greater sense of achievement during the lessons. The other students found the teachers' reluctance to answer a question directly to be an irritation. They all suggested that this was a novel approach that they had not experienced in other lessons, and that they would like to have more lessons of this style.

Another finding of the trial was of a practical nature. It proved difficult to cover the material for each individual CASE lesson in the time available. This is not too surprising, as the original scheme was designed to fit into lessons that were 1 hour and 10 minutes in length, and the lessons in the trial were 50 minutes in length.

Conclusion and implications

Shayer (1999) and Jones and Gott (1998) suggest that the use of CASE as a stand-alone course could be a good way to extend the numerical reasoning skills of the more able students. This is particularly notable as Jerrim and Shure (2016) state that one reason for Wales's poor performance in the PISA tests is that more able students perform less well when compared with those in the rest of the UK. The findings of both the interviews and of the lesson trial carried out suggest that teachers and students find the CASE approach to be effective and engaging in supporting the development of numerical reasoning. The CASE approach makes the reasoning behind the collection and interpretation of scientific data explicit to students and also to their teachers. However, there are challenges to be overcome in fitting the CASE lessons as written into a 50 minute lesson. There also remains the issue of meeting the needs of less able students. Our suggestion is that developing new lessons using the principles of cognitive acceleration within the science curriculum may be a suitable approach to supporting the development of numerical reasoning skills.

Plans for future work

A range of activities based on the underlying principles of the CASE scheme is currently being prepared, which should encourage students to discuss the thinking behind their numerical reasoning. These activities will soon be trialled with students, with the assistance of trainee teachers from Bangor University. Any that are found to be effective will then be shared as examples of good practice as part of a professional development programme for teachers.

Table 4 Change in the numerical reasoning test scores of the intervention and control groups

Group	Initial number of students in the group	Change in numerical reasoning score		
		Mean	Median	Mode
Intervention	51	+3.5	+5	+5
Non-intervention	135	+4.9	+7	+1

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