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Cognitive acceleration through science education

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Introduction

The purpose of this chapter is to review the literature on cognitive acceleration with a view to unravelling potential theoretical explanations for the success of the intervention. Cognitive Acceleration through Science Education (CASE) was the first of the cognitive acceleration (CA) suite of programmes developed at King’s College, London to improve students’ abilities to reason and think. Published as Thinking Science (Adey, Shayer, & Yates, 2003), the school science intervention programme has accumulated evidence on the effects, both on students’ cognitive development and school achievement. Drawing from Piagetian developmental psychology and socio-cultural Vygotskian psychology, the CA programmes are accompanied by a long-term professional development programme for teachers.

This chapter comprises two major sections. The first section maps out the background literature on cognitive acceleration including an examination of the pillars of the cognitive acceleration pedagogy and the professional development programme. The second section looks more closely at the detailed findings of more recent literature and explores possible theoretical explanations including the sociocultural aspects of the pedagogy, metacognition and how recent advances in neuroscience may provide physiological explanations for what happens in the brain during cognitive development.

Background literature and overview of cognitive acceleration

Thinking lessons and activities developed within the context of science and designed to stimulate cognition were piloted in junior high school classes with students aged 11–13, with long-term effects on students’ thinking and achievement with evidence of transfer across the curriculum. The most accessible summaries of the impact of CASE on students are provided.
in Shayer (1999) and Adey and Shayer (1994). The original CASE experiment was conducted from 1984 to 1987 with an experimental/control pre-test, post-test and delayed post-test design. The findings showed both immediate and long-term accelerated cognitive development. Most impressive of the results was that three years after the end of the intervention participating students showed improvements in their GCSE (the UK General Certificate of Secondary Education) grades not only in science but also in mathematics and English. The original experiment included only a small number of students (approximately 130 students in the experimental and control groups) but subsequent experiments with successive cohorts of schools since the 1990s included over 2000 students from 11 schools provide similar findings. These data are, perhaps controversially, indicative of some fundamental changes in students’ reasoning abilities (Adey & Shayer, 2002). Adey and Shayer (2002) argued that rather than students learning science content and processes through cognitive acceleration lessons, the fundamental way the participating students process information is changed. This means they have gained long-term access to ways of thinking, such as being able to understand models, that impacts their learning across the curriculum.

More than ten years ago, Adey and Shayer (2002) wrote that cognitive acceleration ‘has come of age in the sense of growing out from its roots in secondary school science into all areas of the curriculum and across the school age range’ (p. 1). Today, this ‘coming of age’ is continuing with the teaching of thinking becoming more evident in school curricula internationally. For example, there have been two recent studies in Ireland using the CASE curriculum materials, one at the primary to secondary school transition (McCormack, 2009) and one in the early years of primary school (Gallagher, 2008). Science curricula across the world generally state an expectation that students are able to set up and carry out a ‘fair test’ in their science investigations. This forms one part of the development of scientific reasoning in students and these sorts of thinking skills typically form part of the ‘inquiry’, ‘working scientifically’, or ‘investigating’ components of a science curriculum. Along with the need to promote critical and creative, or higher order thinking in students, school curricula specify subject specific content coverage and more generalised skills and attitudes.

Following the evident impact on students of the original CASE, a number of other cognitive acceleration programmes were developed for young children (Adey, Robertson, & Venville, 2002; Shayer & Adey, 2002; Venville, Adey, Larkin, & Robertson, 2003), in mathematics (Shayer & Adhami, 2007, 2010), technology (Backwell & Hamaker, 2004) and the arts (Gouge & Yates, 2002). Recognised as powerful ‘thinking skills’ programmes, the suite of cognitive acceleration programmes was reported in a meta-analysis to show a mean effect size of 0.61 (Trickey & Topping, 2004, in Higgins et al., 2005, p. 31). Cognitive acceleration programmes also have been successfully adapted and trialled in other places in the world including China (Lin, Hu, Adey, & Shen, 2003), Malawi (Mbanu, 2003), Finland (Hautamäki, Kuusela, & Wikström, 2002), Oregon (USA) (Endler & Bond, 2008), Pakistan (Iqbal & Shayer, 2000) and Australia (Oliver, Venville, & Adey, 2012). Even a short intervention using a small number of the CASE materials in Israel was effective in promoting Year 9 students’ reasoning abilities and attainment in science, particularly in regard to the control of variables’ (Babai & Levi-Dori, 2009, p. 445). These studies across the world and at different levels of schooling show that reasoning can be improved as a result of such interventions, to good effect, chiming with what we know about neuroplasticity (Oliver, 2011) a relationship we explore in more detail later in this chapter.

The particular ‘thinking’ lessons that are the foundation of cognitive acceleration programmes are taught separately from the normal school curriculum. These lessons include one or two short activities for students and a detailed lesson plan, which offers guidance and recommendations to the teachers and is particularly helpful as teachers become familiar with the
principles of CA. The full programme of CASE includes 30 ‘thinking’ lessons delivered over two years, usually about one ‘thinking’ lesson every two weeks during school term. Lessons are constructed around reasoning patterns (or schemata) specifically addressed through the lesson activities including controlling variables, ratio and proportionality, compensation and equilibrium to analyse process, using correlation, probability, classification, formal models of thinking and compound variables. The reasoning patterns, first described by Inhelder and Piaget in 1958, as ‘underlying formal operational thinking’ (Adéy, 1988, p. 123) have been used in the CA programmes to construct activities, which stimulate the development of thinking. The lessons within each of the cognitive acceleration programmes spiral through increasing levels of complexity related to the reasoning patterns. In *Thinking Science*, for example, the first five lessons have a focus on the control of variables.

The pillars of cognitive acceleration

Each of the CA lessons has five central stages or pillars: (1) concrete preparation, (2) cognitive conflict, (3) social construction, (4) metacognition and (5) bridging (Shayer, 2003). *Concrete preparation* involves the teacher establishing the nature of the activity, the associated vocabulary and the problem for the students to consider. During concrete preparation, the teacher and students negotiate any ideas associated with the lesson. Students and teachers often refer to this as the ‘doing’ part of the lesson, where data are collected. The *cognitive conflict* of the lesson, draws on the Piagetian idea of equilibration and the Vygotskian idea of a zone of proximal development (ZPD). In this case, cognition is stimulated by the ‘presentation of intellectual challenges of moderate difficulty that must be accompanied by support (or scaffolding) to discuss, question, suggest and problem solve’ (Oliver, Venville, & Adéy, 2012, p. 1397). Students may report ‘this doesn’t make sense’ and this is the driver of cognitive development, as students need to discuss the problem, data or develop an explanation. This *social construction* occurs as students work together in groups, sharing the development of explanations and understandings. The lesson activities contain questions on the worksheets that students work through, which arise from each activity and directly target explanations. Teachers play a key role in establishing good group work, encouraging students to think about and consider a range of possible explanations for the problem. During this stage, the teacher’s role is to listen to the discussion in each group, without interacting with them except to ask a prompting question, such as ‘see if you can find a pattern in the data you have collected’, ‘what that might tell you?’ or ‘how could you explain those results?’ The *metacognition* stage of each CA lesson enables students to articulate and ‘hear’ each other’s solutions to the problem solving and reasoning and once again depends on the skills of the teacher to stimulate and give time for this sort of thinking. For teachers inexperienced to these lessons, it ‘feels’ rather laborious, probing students and asking them for their ideas and explanations but is considered essential as all students contribute their groups’ ideas to the general discussion. Skilful teachers, having heard pivotal ideas emerge in the construction phase of the lesson, will be able to judiciously select students or groups to respond to questions in this phase, to elicit answers to the questions from the most concrete to the more sophisticated levels of thinking. In this way, not only are all students’ ideas welcomed, shared and heard, but they are also able to hear how different answers and explanations vary with different levels of thinking and their own thinking can be clarified or modified (Larkin, 2006). Finally, *bridging*, involves applying the ideas developed to other problems in ‘normal’ science lessons or the real world.

‘Normal’ science lessons are opportunities to draw upon the range of problem-solving strategies and ways of thinking developed during the CA lessons. For example, having completed the
first five of the CASE lessons, students have developed a sound understanding of the control of variables, perform better on a school examination and developed their prowess in thinking with more students using formal operational thinking than in a control group (Babai & Levit-Tori, 2009); in classroom terms, this means that students are able to identify variables as being dependent or independent, describe the relationship between them (positive, inverse, curvilinear), the need to control all variables except one independent variable in order to carry out an investigation.

It may appear that these pillars of cognitive acceleration follow a linear sequence throughout the lesson. In the reality of a classroom, however, teachers move between the different pillars of concrete preparation, activities, small group and whole class thinking, questioning, metacognition and bridging. Some teachers see the different parts of the lessons as ‘acts’ with quite different roles for teachers as students are ‘asked to go beyond their present thinking’ (Shayer, 2003, p. 482). Inevitably, teachers relinquish a traditional approach to the classroom, as they support students’ resolving the conflict inherent in the activities, manage the sharing of ideas from all groups and question to clarify meaning and understanding. Teachers involved in the Cognitive Acceleration through Mathematics Education (CAME) project identified changes in ‘classroom processes and dispositional changes in’ students (Goulding, 2002, p. 117) which may account for the improvements in performance of students on standardised tests.

### Professional learning

Studies looking at the issue of different results from different schools participating in the same CA programme have described the complexity of the schools and how the most successful (in terms of students’ cognitive gains) operate in particular ways: school leaders and administrators support the intervention through enabling teachers to work collaboratively and cooperatively, to develop their knowledge and understanding of the theoretical basis for the intervention (Adey & Shayer, 1990, 1993; Shayer, 2000). Integral to the CA programmes is the ongoing professional development (or learning). Over the two-year programme of CASE, for example, teachers are provided with six days away from school and participate in professional development associated with the preparation, implementation and evaluation of the programme. Time is given to teachers for classroom coaching and participating teachers have a sense of ownership and commitment. The extensive professional development over the period of the intervention provides for teacher learning, reflection and planning (Wilson, 2013).

### Exploring possible explanations for the effects of CASE

Data from the cognitive acceleration programmes have been examined, with suggestions that the science curriculum be redesigned to include the ‘procedural knowledge’ as content and to use the CASE methodology as part of the suite of teaching techniques in everyday use (Jones & Gott, 1998). This position certainly needs to be considered. Is the CA pedagogy just a change in teaching style? Is it the teacher’s approach to questioning or the peer-to-peer mediation that is effective? With evidence of consistent and qualitative improvements in students’ thinking as a result of the CA programmes, greater support for teacher development seems warranted. Critics of the CA programme include those who question the nature of a ‘general processing ability’, whether this can indeed be modified through a targeted intervention programme and whether what is measured in terms of cognitive gains can reasonably be attributed to the intervention programme (Jones & Gott, 1998). These authors argue that there may be other factor/s that could account for the data that the repeated cognitive acceleration studies have shown.
It is unlikely that there is one explanation for the effects of the CA programmes on students’ thinking. Nevertheless, the data prompt us to seek explanations. This section includes a discussion of questions that have been asked of the programme and some of the possible explanations that have been advanced including the issue of student motivation as well as socio-cultural theory, dialogical talk and metacognition as the key pillars of cognitive acceleration that stimulate cognition. Finally, we draw upon insights from neuroscience that have the potential to explain the success of the CA programmes based around the notion that intelligence arises as the brain reasons, plans and solves problems.

Leo and Galloway (1995) argued that there is an absence of a ‘theoretical framework’ to explain the cognitive acceleration research findings. They raised an alternative (or perhaps additional) explanation in terms of students’ motivation to learn. The notion that cognitive acceleration pedagogy may preferentially suit students with a particular motivational style was put forward to explain why some students show greater cognitive gains than their peers in the same classroom environment (Leo & Galloway, 1995). This claim has not been tested and Adey (1996) argued that Leo and Galloway failed to adequately argue for motivation style as an explanation of the CASE results because it is not easy to operationalise and not easily tested. Shayer (2003) disputed the lack of theoretical framework arguing that the pillars of cognitive conflict, social construction and metacognition were deeply embedded in a constructivist epistemology and research in this paradigm offered theoretical explanations for the findings. In research that brought both the constructivist and motivation theoretical claims to bear, McLellan (2006) found that the cognitive gains are also matched by gains in motivation exhibited by most students, which augur well for both scholastic achievement and attitudes to school. However, the relationship between motivation and cognitive gains is more complex than a simple one-way relationship, with those making the greatest cognitive gains also showing a decrease in motivation. This apparent motivation ‘trade-off’ at the top end of the cognitive spectrum is of concern and warrants greater research (McLellan, 2006).

**Sociocultural explanation**

The Vygotskian theory that underpinned the development of the suite of CA interventions resulted in the incorporation of ‘social construction’ in the form of group work into the CA pedagogy. Sociocultural theory provides a strong potential explanation for why the research around the CA interventions has demonstrated intellectual growth. Much research has been conducted in recent years from a sociocultural perspective that emphasises the importance of language as a cultural and psychological tool that can influence the development of children’s reasoning (Mercer, 2010). For example Mercer and Littleton (2007) draw on extensive research to argue that classroom talk is critical to children’s intellectual development during the school years. Further, they argue that information about how to create situations that stimulate quality talk is of enormous practical value to teachers. Mercer and Littleton’s own data show that ‘when teachers focus on the development of children’s language as a tool for reasoning, this can lead to significant improvements in the quality of children’s problem solving and academic attainment’ (p. 3). This sort of classroom dialogue is a central component of the CA programmes.

There has been little qualitative research on the nature of the discourse and interaction between students while they are engaged in cognitive acceleration activities. One study (Venville et al., 2003), found that students participating in thinking lessons specifically designed from the CASE methodology for Year 1 (5- and 6-year-old students) compared with regular curriculum lessons on a similar subject were more frequently involved in: explaining their ideas and other students’ ideas; highlighting discrepancies between group members’ ideas; adopting or changing...
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their own ideas when a better idea is presented by another group member; making suggestions for solving problems; and, building on other students’ ideas.

Wall (2002) explored 5 to 6 year olds’ perceptions of the group work of the CASE intervention and found that CASE groups, compared with non-CASE groups of students more frequently mentioned thinking and discussion-type behaviours and more frequently used terms related to thinking, sharing, listening and working together. Further, many of the comments on communication indicated the CASE students perceived these activities in terms of social, rather than task or work orientations. These findings resonate with those of Mercer and Littleton (2007) who reported ‘indicator’ words that showed how participating children’s talk changed after a programme, called Thinking Together, to teach them how to use high quality talk in groups. The key terms were those that qualitative analysis had shown were associated with the use of exploratory talk and included ‘because’/’cos’, ‘agree’ and ‘I think’. The group work in the CASE intervention and the Thinking Together intervention can both potentially be explained by the notion of exploratory talk (Wegerif, Mercer, & Dawes, 1999) because group members engage critically but constructively with each other’s ideas (Mercer & Littleton, 2007). In both programmes, students, even very young students, are able to listen to and critique each other’s ideas and engage with the process of collective problem solving. They are able to do this because they are explicitly taught how to do it, their teachers are pedagogically able to support children and they are involved in group activities that were designed to encourage thinking (Mercer & Littleton, 2007; Shayer & Adey, 2002).

Mercer and Littleton (2007) claim the collective results from a number of their colleagues’ studies ‘provide evidence of change in both group and individual reasoning’. They argue, therefore, that these data ‘provide further and stronger support for the sociocultural hypothesis that using language as a tool for reasoning collectively can influence the development of individual thinking and learning’ (p. 93). The analysis of the Thinking Together programme provides evidence to support Vygotsky’s theorised relationship between language use, social interaction and intellectual development (Mercer & Littleton, 2007) and supports a sociocultural explanation for CA interventions. There is considerable scope for more research in this area around the construction zone during the group work of CA lessons.

Metacognition explanation

Metacognition is another pillar of the CA methodology that provides a possible theoretical explanation for the findings of the suite of CA research projects. It was included as an original pillar for the CASE pedagogy because Adey and Shayer considered metacognition ‘a feature of the development of higher order thinking which seems to carry almost universal support from cognitive psychologists’ (Adey & Shayer, 1994, p. 67) and, therefore, likely to be an essential element of any programme for developing thinking skills. Larkin (2010) points out that metacognition remains a construct that is largely studied by psychologists rather than by educational theorists and that there is little systematic research on the complex interactions that specifically impact on metacognitive development. However, a number of researchers have indicated connections between metacognition and critical thinking (Magno, 2010), problem solving (Lai, 2011), and persistence (Martinez, 2006) all of which suggest that metacognition is an important contributor to the success of CASE.

Larkin (2002) investigated the metacognitive experiences of the 5- and 6-year-old children participating in the CASE programme for Year 1s. Her analysis showed that the CASE lessons included more metacognitive activity and metacognitive activity of a qualitatively different type compared with control lessons on a similar mathematical concept. In the CASE activities, the focus was on the problem-solving process; and in the control lessons, the focus was on the
successful calculation of number. In the CASE lesson the teacher modelled the language of learning including explaining thinking and engaging in planning and evaluating strategies by asking questions such as, ‘What do you think we’re going to have to think about?’, ‘How do you know that?’ and, ‘What could you do if you’ve got problems?’

Larkin (2010) argued, particularly in the case of young children, that metacognition is developed through collaboration on a joint task. She provided examples where the teachers participating in her study fostered skills in their students including thinking about themselves as thinkers and ruminating about the nature of knowledge and evidence. These skills are particularly important for scientific thinking. ‘Understanding the need to provide plausible explanations for phenomena and to rate and compare explanations are foundation stones of science’ (p. 53). Larkin concluded after more than 70 hours of observation over one year, that the CASE research programme provided a wealth of examples of young children engaging in metacognitive dialogues while working through challenging group tasks. She contended that metacognition is constructed socially through engagement on the task and not simply through reflection after completion of the task.

Larkin (2010) explained that inhibitory control, an executive control mechanism in the prefrontal cortex of the brain, is responsible for metacognition. She speculated that being able to inhibit our initial response is important in many areas of learning, in particular conceptual change, because we need to be able to inhibit our naïve ideas and accept the plausibility and fruitfulness of new, more powerful ideas. Being able to inhibit our initial response enables effective planning rather than jumping straight in; to consider whether our answers are appropriate; and allow us to think of the sources of knowledge and evidence we are being presented with. All these ideas point to the pillar of metacognition as an important factor in the success of the CA suite of programmes.

A neuroscience perspective

While the data suggest that the cognitive acceleration programmes exert both a long-term and transfer effect, explanations for these impacts are less obvious to identify: perhaps students have become more motivated over the intervention period, more comfortable with dealing with uncertainty, more confident in their own thinking.

More tangible potential explanations come from recent developments in neuroscience which confirm that our understandings of the workings of the brain can inform teaching and learning (Dubinsky, Roehrig, & Varma, 2013). Since the development of the first CA programmes, there are now greater understandings of the ways that the brain develops and the implications that these understandings have for pedagogy. Dubinsky et al. (2013) listed the core neuroscience concepts and each core concept’s general implications for teaching and learning. These core concepts are very interesting when considered within the context of cognitive acceleration programmes and the underpinning theory. For example, one of the core concepts is that neurons communicate using both electrical and chemical signals. The implication of this core concept is the notion of plasticity, the cellular basis for learning and memory. It implies that communication between the neurons is strengthened and weakened when we use them more or less frequently. We can extrapolate this simple core concept of neuroscience to support the notion that practicing the schema in CASE lessons possibly strengthens neuronal pathways that enable students to better think in sophisticated, schema-based ways such as inverse proportionality and equilibration. Plasticity describes the physical synaptic strengthening as learning occurs with repeated use of neuronal pathways. Students knowing about neural plasticity appear to be ‘prepared to struggle to learn difficult content’ (Dubinsky et al., 2013, p. 319; Oliver, 2011). Teachers using CASE in schools report a similar finding, allowing ‘students to struggle with an explanation’ (Dullard & Oliver, 2012, p. 10).
Another important core concept from neuroscience that is consistent with the findings of CASE is that ‘intelligence arises as the brain reasons, plans and solves problems’ (Dubinsky et al., 2013, p. 318). This core concept is argued to account for intelligence, or the accumulated history of activity in the brain synapses. ‘In other words, practicing creative or deductive thinking facilitates further use of these strategies’ (Dubinsky et al., 2013, p. 218.) Adey and Shayer (e.g. 2002) have long argued that their findings support the notion of a general processor or general intelligence that has wide ranging influence on academic achievement.

One of the most interesting core concepts from neuroscience is that ‘the brain makes it possible to communicate knowledge through language’ (Dubinsky et al., 2013, p. 318). It could be argued that the promotion of communication in groups through the social construction pillar of the CA pedagogy fosters the exchange of information and creative thought by exercising and developing neural pathways. The wide-ranging findings from the emerging field of neuroscience offer much potential for physiological explanations for the findings of the CA programmes and also potential to improve and refine the CA pedagogies.

**Conclusion**

Recent research shows that the cognitive level of students is, in general, lower now than a generation ago (Shayer, Ginsburg, & Roe, 2007; Shayer & Ginsburg, 2009). It appears unlikely that large numbers of students are cognitively ready and thus able to engage with the demands of the science curriculum. The problem of a curriculum out of step with the levels of thinking of the student population can only lead to further disengagement or compromising the curriculum by reducing the cognitive demands of the curriculum. There is a need to bring to the attention of policy makers, these sorts of education interventions that have long-lasting impact on students’ learning. The long-term costs of lower educational standards are well reported (OECD, 2010). There is, of course, another solution that involves cognitive acceleration.

This chapter has provided an overview of the literature that forms the research tradition of cognitive acceleration. The findings from this research tradition show that the cognitive acceleration pedagogy impacts positively on student cognition and academic achievement. The pedagogical pillars of the original cognitive acceleration programmes including social construction and metacognition provide compelling theoretical explanations for the success of the CA interventions. Findings from the emerging field of neuroscience provide potential physiological explanations about how the theoretical constructs that inform the CA pedagogy may have real impact on students through development of neuronal pathways in the brain.

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