LEARNING AND FEARING MATHEMATICS: INSIGHTS FROM PSYCHOLOGY AND NEUROSCIENCE

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Dr Sarah Buckley is a Research Fellow at ACER. Her PhD in psychology investigated adolescents' mathematics anxiety and the role that motivation and peer networks have in its development. The project drew on diverse theories including those from psychophysiology, cognitive and social psychology and social network approaches. Sarah was invited to present her work at national and international conferences and in 2008 won the AARE's Australian Postgraduate Student Travel Award. In 2012, Sarah was asked to write an opinion article for *The Age* newspaper on the phenomenon of mathematics anxiety.

Sarah is a member of the National Surveys team at ACER and has contributed to a range of projects such as the Programme for International Student Assessment and the Trends in International Mathematics and Science Study. Sarah has also been part of several projects focused on Indigenous education including the Longitudinal Study of Indigenous Children.

In addition to her time at ACER, Sarah has worked as a data analyst for the education department at Monash University and as a research assistant and tutor in the psychology department at the University of Melbourne. Sarah also has three years experience working as a teacher's aide in high school classrooms.

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Dr Kate Reid is a Research Fellow at ACER. She completed her master's degree in psychology and PhD at the University of Melbourne, undertaking research into mathematical reasoning among preschool children. Her research applied an individual differences perspective to understanding learning processes in the acquisition of early number and measurement concepts. Through her research, she gained extensive experience in a range of early childhood settings, designing mathematics activities and interviewing children aged 3–6 years.

Kate has diverse research experiences, including quantitative and qualitative research projects for evaluations of government initiatives and community-based programs, and has published academic research in the area of higher education. Kate has extensive experience in research and teaching in higher education, having taught at undergraduate and postgraduate level in developmental and cognitive psychology, statistics and organisational behaviour.

Since joining ACER, Kate has continued her interest in the learning of preschool children through her work on the ACER research project, Longitudinal Literacy and Numeracy Study: Transitions from Preschool to School. She developed and trialled for this project numeracy activities suitable for five-year-old children, and was involved in the national implementation of the project in late 2012. Most recently, Kate undertook a review of effective approaches to numeracy intervention among children in the early years of schooling.

ABSTRACT

Researchers investigating mathematical development do so from different perspectives. Disciplines such as education, psychology and neuroscience have focused on mathematical learning and motivation, but research in these fields has tended to be conducted independently. Although different research strategies and methodologies are employed in each discipline, similar research questions inform these approaches and findings from these areas are complementary. In this session, we consider two examples from the field of research on mathematical development and present some relevant research developments from psychology and neuroscience. Our first example focuses on how very young children begin to acquire mathematics concepts. In our second example, we discuss the phenomenon of mathematics anxiety and its impact on children's learning of mathematics. Our overarching goal is to illustrate how findings from psychology and neuroscience may be used to better understand the processes underlying children's learning of mathematics, and to suggest how these findings might be applicable to mathematical behaviour in the classroom.

INTRODUCTION

There is much interest in the potential for neuroscience research findings to significantly affect classroom practice. Some researchers argue that direct application of neuroscience findings to educational practice is difficult because our understanding of the brain and brain development is still fragmentary (Bruer, 1997) but considerable interest remains in the field of education in how findings from neuroscience might inform teaching. If research findings are to be applied, they must be critically evaluated. Educational practitioners need some assurances that robust research evidence underlies teaching practices and programs derived from neuroscience findings.

In this session, we argue, in line with Bruer (1997), that cognitive psychology is the field that connects the application of neuroscience findings to the field of education. Furthermore, we provide evidence of how an interdisciplinary approach could be used to understand learning in mathematics. There is evidence of cross-field integration in describing children's early mathematical development, and proposing and testing models of mathematical cognitive development from infancy to the early years of primary school. Findings from different disciplines have also been applied to understanding barriers to school-based learning, which includes the phenomenon of mathematics anxiety, commonly reported by secondary school students. Discussion of these two related areas is intended to demonstrate the contribution that education, cognitive psychology and neuroscience together can make to informing teaching practice and interventions in mathematics.

EARLY NUMERICAL ABILITIES AND DEVELOPING NUMBER SENSE

There is considerable evidence that the ability to understand simple number relationships is early developing, or even innate (McCrink & Wynn, 2004; Wynn, 1990, 1992a, 1992b, 1995). Studies of infants imply that they may have a preliminary understanding of cardinal relationships (concepts of the number of objects) (Antell & Keating, 1983; Starkey & Cooper, 1980; Starkey, Spelke & Gelman, 1990) and of transformations to numbers (Wynn, 1992c, 1992d, 1995). These abilities were thought to be limited to very small numbers (up to three or four), but more recent evidence suggests that infants are also sensitive to the results of large number transformations, which may reflect an approximate number system. Evidence of a pre-verbal number sense among human infants and animals implies that mathematical competence is initially independent of language. Number sense skills include an ability to rapidly identify small numbers, recognise number order, reason about simple transformations (for example, adding and subtracting one), exhibit counting skills and apply counting to solve number problems. Number sense capabilities are related to achievement in school (Bisanz, Sherman, Rasmussen & Ho, 2005; Mix, Huttenlocher & Levine, 2002), but there is significant individual variation in the development of children's number sense before school, and evidence that some children find it difficult to connect informal knowledge with school mathematics (see, for instance, Carraher, Carraher & Schliemann, 1985; Carraher & Schliemann, 2002; Nunes, Schliemann & Carraher, 1993).

Among preschool children there is similar evidence for early informal understanding of number concepts for both small and large sets of objects that is independent of the development of counting (Canobi & Bethune, 2008; Slaughter, Kamppi & Paynter, 2006). Gelman and colleagues' extensive research on counting development suggests that understanding the principles of counting guides children's whole number development (Gallistel & Gelman, 1992; Gelman, 2000). Evidence of principled understanding is thought to be evident in children's capacity to detect violations of the counting principles, even when they cannot count (Gelman, 1980; Gelman & Gallistel, 1978; Gelman & Meck, 1983, 1986; Gelman, Meck & Merkin, 1986).

This brief description of key research in mathematics has implications for early mathematical learning. It is argued that humans possess specialised mechanisms for processing information about numbers. A specific mechanism for discrete number suggests that difficulties could arise in extending learning from whole number concepts to those involving rational numbers. From a psychological perspective, early reasoning about fractions is difficult because it is incongruent with a system supporting natural number development (Gallistel & Gelman, 1992; Gelman & Meck, 1992; Hunting & Davis, 1991; Mack, 1995; Sophian, Garyantes & Chang, 1997). This conflict is evident in students' extension of whole number principles to fraction reasoning (for example, believing ¼ is bigger than ⅓ because the denominators are compared as whole numbers).

Neuroscience and neuropsychological findings suggest that both specialised systems for processing number and separable systems for processing small and large numbers can be independently impaired (Feigenson, Dehaene & Spelke, 2004; Hyde & Spelke, 2009). The intraparietal sulcus, which shows activation in numerical estimation tasks, is believed to be the location of the approximate number system (Feigenson et al., 2004). Although much of this work to date has been conducted with adults, more recent research using minimally invasive techniques (such as EEG) with infants also suggests independent systems for small and large numbers (see, for instance, Hyde & Spelke, 2011).

Much of the evidence discussed supports the proposition of a number sense system from which mathematics develops. Dehaene (2001) argued that number sense has a specific cerebral location (the intraparietal cortex of both the left and the right hemispheres), but that this area is a part of a complex distributed system of connections for processing number. Specific patterns of activation depend on the mathematical activity involved (for instance, calculation versus numerical comparison) (Dehaene, Molko, Cohen & Wilson, 2004). Number sense is of interest as a critical feature of normal mathematics learning, and as a probable source of deficit for those with more severe mathematical difficulties (Gersten & Chard, 1999). Children with dyscalculia, for instance, evidence structural and functional deficits of the intraparietal sulcus (Dehaene et al., 2004). Though any deficiencies in initial number sense may constrain early learning, these limits are not fixed. Training in mathematics problems is associated with pronounced changes in patterns of brain activation and corresponds with variation in behavioural data (such as reduced reaction time and higher accuracy) (Zamarian, Ischebeck & Delazer, 2009). Moreover, different learning methods (learning by rote versus learning strategically) result in different patterns of brain activation (Delazer et al., 2005). Supplemented with behavioural data on better performance in strategic learning conditions, these data provide evidence that different teaching methods for mathematics lead to distinct behavioural and structural outcomes.

BARRIERS TO DEVELOPING MATHEMATICAL PROFICIENCY: MATHEMATICS ANXIETY

A significant barrier to learning in the mathematics classroom is anxiety. Anxiety is a widespread emotion in schools and in the community, is negatively associated with school achievement and is exacerbated by a negative culture surrounding mathematics (Ashcraft & Ridley, 2005; Hembree, 1990; Ma, 1999; Ma & Xu, 2004; Meece, Wigfield & Eccles, 1990; Wilkins, 2000). Some theorists suggest that mathematics anxiety is a consequence of struggling with poor mathematics ability (Ashcraft & Kirk, 2001). There is evidence that students who have dyscalculia report high levels of mathematics anxiety (Rubinsten & Tannock, 2010) but research has shown that anxiety can affect learning in two broad ways. Firstly, at the state or on-task level, mathematics anxiety can impair performance; secondly, as a trait, it can act like an attitude, directing students away from participation in activities and career pathways that involve mathematics.

Psychology and neuroscience provide models of the state-based effects of anxiety. According to psychological theory, a primitive biological system – the autonomic fight-or-flight response – is at the centre of the experience of anxiety and primes the body for action in threatening situations (LeDoux, 1996). Mathematics provides a threatening situation for students who report high levels of mathematics anxiety. Psychology also offers a way to understand how certain situations can evoke anxiety in one student and not in another. Izard (2007) proposed that *emotion schemas*, or 'complex emotion-cognition-action systems', are key components of the motivation and regulation of emotions and are activated when an individual appraises a situation (p. 265). These schemas are shaped by previous experiences and cultural factors. Cognitive psychology also highlights the role of *attentional biases* in making an anxious individual hyper-vigilant to threatening stimuli (Hofmann, Ellard & Siegle, 2012).

These concepts have been integrated with neuroscience research. Studies have shown that attentional biases to threatening information are activated just milliseconds after stimuli are presented and are associated with more activation in the amygdala (a part of the brain thought to be involved in processing negative emotions), and a diminished role of the prefrontal cortex (which helps to regulate emotional responses and inhibit fear-based reactions) (Bishop, 2007; Young, Wu & Menon, 2012). Recently, Young, Wu and Menon (2012) found this type of neural activation pattern in mathematically anxious children as young as seven. Together these findings suggest that mathematics anxiety predisposes students to be hypersensitive to mathematical stimuli, to experience fear almost automatically after they encounter mathematics and to be less capable of recruiting strategies to control this fear. The long-term implication of this process is students will learn to avoid situations that involve mathematics.

Evidence that mathematics anxiety has a direct or on-task effect on performance can also be found in cognitive psychology and neuroscience research. Ashcraft and Kirk (2001) proposed an online mathematics anxiety model wherein intrusive, negative thoughts about performance disrupt cognitive functioning by interfering with working memory processes. Several studies examining the effects of mathematics anxiety on working memory support Ashcraft and Kirk's model (Beilock, Kulp, Holt & Carr, 2004; Hopko, Ashcraft, Gute, Ruggiero & Lewis, 1998; Hopko, McNeil, Gleason & Rabalais, 2002; Kellogg, Hopko & Ashcraft, 1999). Furthermore, Lyons and Beilock (2012) demonstrated that the disruption of working memory processes was associated with more activation in a network of the inferior fronto-parietal regions of the brain. They proposed that their findings point to 'educational interventions which emphasise the control of negative emotional responses to math stimuli' (p. 2109).

These studies from cognitive psychology and neuroscience illustrate how mathematics anxiety operates at the state level but they do less to explain the origins and development of anxiety. If interventions to reduce anxiety must help students to control their emotional reaction to mathematics, the factors that lead to children feeling negatively towards the subject must be identified. Educational and social psychology research provides more insights into the aetiology of anxiety. Cemen (1987) proposed that mathematics anxiety is a product of dispositional, environmental and situational forces. Dispositional factors can be thought of as what the student brings to the classroom. Important antecedents that are considered to be external to the student are environmental, such as teachers and peers, and more immediate, situational forces, such as the specific features of a mathematics task (Baloglu & Kocak, 2006). The focus here will be on the role of teachers, peers and gender socialisation as environmental and situational forces that operate in the classroom.

Research supports the notion that the development of mathematics anxiety is influenced by multiple factors. Studies have found that a high proportion of preservice mathematics teachers report elevated levels of anxiety, with more anxious female teachers more likely to have students with lower achievement and negative gender stereotypes about mathematics (Beilock, Gunderson, Ramirez & Levine, 2010; Hembree, 1990; Uusimaki & Kidman, 2004). Frenzel, Pekrun and Goetz (2007) showed that peer esteem, measured by items such as *'most of the students in my class think mathematics is cool'* was negatively related to anxiety; students who believed that their classroom reflected a negative peer culture towards mathematics reported higher levels of mathematics anxiety. These results suggest that the role of socialisation in the development of students' mathematics identity is important, a process also emphasised in research targeting the relationship between gender and mathematics. In particular, the effect of negative stereotypes (referred to as *stereotype threat*) has been suggested as an explanation for girls' under-representation in mathematics fields and gender differences in mathematics anxiety (Tomasetto, Romana Alparone & Cadinu, 2011). National results from the 2003 Programme for International Student Assessment (PISA – Thomson, Creswell & De Bortoli, 2004) showed that Australian 15-year-old girls reported higher mathematics anxiety levels than males. Furthermore, a New South Wales study showed that the number of girls choosing to enrol in mathematics in their final years of schooling was declining at a faster rate than boys (Mack & Walsh, 2013).

These findings in relation to gender, peers and teachers suggest directions for intervention strategies. They reveal that classroom culture has the potential to influence the development of mathematics anxiety and dealing with these factors could improve students' attitude and thus achievement in mathematics. Challenging gender stereotypes and negative peer culture within the classroom are some examples of ways to move in this direction. From this type of intervention, students can develop more control over their negative emotional reactions to mathematics and inhibit the negative influence of anxiety on performance and career choices.

CONCLUSIONS

With increased interest in neuroscience findings, researchers from related disciplines have begun to supplement existing knowledge about learning with findings from neuroscience. This brief review has illustrated how existing research from education, psychology and neuroscience can provide a basis for better understanding children's learning of mathematics. Using children's early number sense and mathematics anxiety as examples, we have argued that psychology, in particular, provides frameworks for integrating neuroscience and education research. This type of interdisciplinary approach can suggest strategies for both improving mathematical learning among young children and providing interventions when students' achievement in mathematics is not as expected.

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