



Changing Minds: Discussions in neuroscience, psychology and education

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Counting on it: Early numeracy development and the preschool child

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Changing minds: Discussions in neuroscience, psychology and education

The science of learning is an interdisciplinary field that is of great interest to educators who often want to understand the cognitive and physiological processes underpinning student development. Research from neuroscience, psychology and education often informs our ideas about the science of learning, or 'learning about learning'. However, while research in these three areas is often comprehensive, it's not always presented in a way that is easily comprehensible. There are many misconceptions about neuroscience, psychology and education research, which have been perpetuated through popular reporting by the media and other sources. These in turn have led to the development of ideas about learning and teaching that are not supported by research. That's why the Centre for Science of Learning @ ACER has launched the paper series, *Changing Minds: Discussions in neuroscience, psychology and education*.

The *Changing Minds* series addresses the need for accurate syntheses of research. The papers address a number of topical issues in education and discuss the latest relevant research findings from neuroscience, psychology and education. *Changing Minds* does not provide an exhaustive review of the research, but it does aim to provide brief syntheses of specific educational issues and highlight current or emerging paradigms for considering these issues across and within the three research fields. The paper series also provides teachers, school leaders and policymakers with accessible multidisciplinary theory and research that can be used to reflect on educational practice and policy.

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Background

Children think mathematically long before they start school. Before children start learning mathematics at school, they show informal understanding of many numeracy concepts (Song & Ginsburg, 1987; Sophian, Harley, & Manos Martin, 1995). This is informal numeracy knowledge, that is, skills that children develop before starting school that do not depend on written mathematical notation (Purpura & Napoli, 2015). For example, children's numeracy knowledge is evident in their developing counting skills. It is also evident in their capacity to compare, share, order, estimate and calculate different quantities. Fundamental skills in recognising and responding to numerical cues are apparent in infancy, and, at a very basic level, may be innate (Wynn, 1995a; Xu, Spelke, & Goddard, 2005).

Early numeracy skills influence achievement in school mathematics (Malofeeva, Day, Saco, Young, & Ciancio, 2004; Purpura & Napoli, 2015; Starkey, Klein & Wakeley, 2004). Understanding the importance and development of preschoolers' numeracy skills is fundamental for those involved in early years education so they can support and encourage children to develop their skills in early learning contexts, and provide appropriate school-entry teaching and learning (Floyd, Hojnoski, & Key, 2006).

This review synthesises current research from neuroscience, psychology and education to highlight some key findings in the development of preschool children's early numeracy skills. The review focuses on three areas:

- origins of preschoolers' numeracy skills
- important numeracy skills in preschoolers' development, and
- connections between preschoolers' numeracy skills and their later school achievement.

The purpose of the review is to highlight a selection of relevant research findings. It is not intended to be an exhaustive review of the literature. The aim is to emphasise the significance of preschool children's early numeracy development and to argue for the importance of fostering early numeracy in early childhood contexts.

Origins of preschoolers' early numeracy skills

Can infants process numbers?

Researchers have tried for some time to determine whether infants have a basic awareness of numbers. Such research, largely undertaken in psychology, has focused on demonstrating that infants, some as young as a few days old, can perceive numbers.

Researchers have argued that the human brain has specialised mechanisms for processing quantity that, at a very basic level, are innate, rather than a product of language development or culture. These basic skills are independent of language because they can be found in preverbal infants and also among animals. For instance, rhesus monkeys can be trained to order numbers (Brannon & Terrace, 2000), rats and pigeons can be trained to press a lever a particular number of times to obtain food, and chimpanzees reliably choose one of two trays with the greater number of food items (Gallistel, 1989).

Investigations in developmental and cognitive psychology have aimed to identify whether infants could detect changes in numbers. Across different experimental scenarios, researchers used infants' tendency to 'habituate' to particular objects and events (that is, lose interest over time), followed by increased attention to novel objects and events (measured as increased looking time). They found that infants can detect changes in small numbers of up

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to about five – this is the so-called subitising range in which the number of objects can be recognised immediately without conscious counting (Wynn, 1995b). For instance, infants (of an average age of 22 weeks) lost interest in a small number of dots (two or three) but looked significantly longer when a new array was presented (either three or two) (Starkey & Cooper, 1980).

Infants can also detect differences between large numbers. Six-month-old infants differentiated between displays of eight and 16 objects, even when they controlled for other factors, such as area and density, which could give cues to number differences (Xu & Spelke, 2000). Later studies showed that these abilities are not limited to visual displays, with infants discriminating differences between small (vanMarle & Wynn, 2009) and large numbers of sounds (Lipton & Spelke, 2003). Infants also discriminate different numbers of actions. For instance, Wynn (1996) showed that six-month-old infants differentiated between the number of jumps a puppet made (two compared with three).

Other research suggests that infants' number sense extends from simple number discrimination to more complex awareness of ordinal relationships.

Other research suggests that infants' number sense extends from simple number discrimination to more complex awareness of ordinal relationships (numbers ordered by size) and even the results of simple calculations. Research suggests that by 11 months, infants can identify when a sequence of ordered numbers reverses from a small to large ordering, to a large to small ordering (Brannon, 2002). Infants aged 11 months shown an ascending sequence of two, four and eight black squares looked significantly longer at a novel descending sequence of 12, six and three black squares compared with the ascending sequence three, six and 12 (Brannon, 2002). Other research suggests these skills may be evident even earlier, with seven-month-old infants successfully detecting reversals in ordinal relationships (Picozzi, de Hevia, Girelli, & Cassia, 2010).

Infants also seem to recognise when the results of simple number transformations are correct or incorrect. In a series of experiments, Wynn (1992) showed five-month-old infants the outcomes of simple addition and subtraction of objects where the outcome was correct ($1 + 1 = 2$; $2 - 1 = 1$) or incorrect ($1 + 1 = 1$; $2 - 1 = 2$). For the addition problem, a single doll was placed on a small stage. A screen came up and the infants saw another doll enter the stage and move behind the screen. When the screen dropped, there were either one or two dolls left on the stage. Across several studies, Wynn showed that four- and five-month-old infants looked significantly longer at incorrect outcomes than they did at correct outcomes, suggesting they were surprised when the outcome was incorrect, as it was unexpected.

More recent studies suggest that infants also differentiate between expected and unexpected outcomes for large number calculation. Nine-month-old infants in another study looked significantly longer at incorrect outcomes of large number addition ($5 + 5 = 5$) and subtraction ($10 - 5 = 10$) than they did at correct outcomes (McCrink & Wynn, 2004).

Based on this body of psychological research, researchers concluded that infants can process number. Furthermore, researchers have inferred different cognitive models of how infants and young children process number, including the likelihood there is one system for processing small, exact quantities and a separate system for estimating approximate quantities (Feigenson, Dehaene, & Spelke, 2004).

What brain processes occur when infants discriminate number?

Neuroscience techniques have been used to identify the brain processes operating when infants discriminate number. These studies have combined the experimental methods of developmental and cognitive psychology with neuroscience techniques like electroencephalogram (EEG). EEG captures the brain's electrical activity in

response to particular events through electrodes attached to the scalp. EEG does not provide as much detail on brain structure as techniques like Functional Magnetic Resonance Imaging (fMRI), but it does give a general idea of the regions of the brain that are active during specific tasks.

Applying this neuroscience lens has built on existing knowledge about young children's responses to number. Such research has demonstrated that electrical activity in the infant brain changes when exposed to number changes, and that these changes in electrical activity are different from responses when only the type of object changes.

One study showed that the electrical activity in the brain changes when three-month-old infants see an unexpected number of objects (Izard, Dehaene-Lambertz, & Dehaene, 2008). When they see an unexpected object, the brain's electrical activity also changes, but different regions of the brain are active. This is further evidence of a specialised brain/neurological system for processing number.

Other researchers working with infants have demonstrated similar effects when investigating changes in the brain's electrical activity in response to expected and unexpected outcomes of small number calculation, with significant negative voltages measured on unexpected (e.g. $1 + 1 = 1$) compared with expected outcomes (e.g. $1 + 1 = 2$) (Berger, Tzur, & Posner, 2006).

What areas of the brain respond to numerical information?

More recently, there has been a great deal of interest in searching for specific areas of the brain that might respond to numerical information.

Research has identified the intraparietal sulcus (IPS) – a groove on the surface of the brain that divides the parietal lobe into two parts and is an area of the brain that is active in visual, motor and attentional processes – as an important area for processing specialised numerical information (Grefkes & Fink, 2005). For instance, a consistent finding in mathematics cognition research is that when adults judge the distance between two numerals, reaction times are faster and more accurate for numbers that are further apart, and faster for smaller numbers than larger numbers (Ansari, 2008; Feigenson et al., 2004).

Recent fMRI studies have shown that activation in the IPS decreases as the distance between numbers increases; yet this relationship is not evident among children with developmental dyscalculia (Ansari, 2008). Developmental dyscalculia is a learning disorder – estimated to affect less than five per cent of the population – that severely affects ability to process numerical information, and to calculate and learn arithmetic facts, despite normal intelligence (Bugden & Ansari, 2015).

As the IPS is active across different mathematical tasks, it is not possible to conclude that there is a dedicated area of the brain responding only to information about numbers. Some single cells in the IPS of macaque monkeys only respond when numerical information is presented, others respond only when information about length is presented, while others respond to both (Ansari, 2008). More work is required specifically with children to better understand the origins of both normal and abnormal mathematical development.

Neuroscience's contribution to understanding early mathematical learning is also largely focused on understanding basic numerical processes, with less focus on understanding higher order mathematical thinking (Grabner & Ansari, 2010). At present, much of the research focused on developmental disorders of mathematical ability relies on findings from adults to interpret children's performance patterns. This, Ansari (2010) has argued, relies on three assumptions that may be misleading where childhood mathematical development is concerned:

- Profiles of mathematical strengths and weakness are stable over time, and they do not vary with development.
- Areas of the brain activated during mathematical tasks are similar for children and adults. However, the pattern of neuronal connections likely varies substantially with development and for children with different mathematical difficulties.
- Similar performance on mathematics tasks equates to similar underlying brain activation. However, such a one-to-one mapping between behaviour and brain activation is not always evident (Ansari, 2010).

What does the research tell us?

Research from developmental and cognitive psychology has yielded significant evidence that a basic capacity to respond to numerical information is present from infancy. Neuroscience has provided complementary evidence of structural location and changes in brain activity when infants detect changes in number. Such evidence shows that infants have a basic predisposition towards processing numbers, but this should not be interpreted as a fixed capacity for developing mathematical understanding. Rather, the research evidence suggests that a foundation is present very early that may provide direction for children as they grow and develop their numerical skills.

Important numeracy skills in preschoolers' development

Before starting school, there is substantial growth in preschoolers' numeracy skills. Such informal knowledge about numbers is often referred to as 'number sense'. Number sense can be defined as the flexible use of numbers to compare, recognise patterns and solve problems (Gersten & Chard, 1999).

Research in neuroscience has suggested that the intraparietal cortex of both the left and right hemispheres of the brain has a specific number sense role (Dehaene, 2011). Yet, the processing of number in the brain is enormously complex. These brain regions do not work in isolation, but are part of a distributed neural system of connections for number processing. Research conducted primarily with adults shows brain-activation patterns depend on the task being completed, with differences, for example, between calculation activities and number comparison tasks (Dehaene, Molko, Cohen, & Wilson, 2004).

How do preschoolers show number sense?

Children show their number sense in many everyday problem-solving situations involving numbers and measurement. They may reason about who has more or less, devise strategies for creating equal shares of countable objects or amounts, or use counting in a range of situations to reason about a single group of objects or to compare two groups. Children informally build these skills in their everyday interactions with carers and with other children, and they can be encouraged to develop their understanding in play situations.

Griffin (2004) has argued for specific number sense content for the typical five-year-old child. She argues that well-developed number sense involves:

- knowing numbers indicate quantity and thus have a magnitude
- understanding and using relative terms such as more, less, bigger and smaller
- knowing numbers in the counting sequence have a fixed position
- understanding the sequence of numbers, e.g. three comes before four
- knowing higher numbers reflect greater quantities, e.g. four is greater than three
- knowing each count term represents a unit increase (Griffin, 2004, p. 174).

Researchers have now recognised that the emergence of counting skills is a significant conceptual development.

While the definition of number sense has been contentious, what is not disputed is the substantial growth in early numeracy skills prior to a child beginning school (Howell & Kemp, 2010). For instance, children's counting skills develop substantially during preschool. Counting was initially regarded as a rote activity for preschoolers, with little relevance for children's developing thinking skills. Researchers have now recognised that the emergence of counting skills is a significant conceptual development, which provides a strong foundation for developing more complex mathematical skills.

What are the three whole-number counting principles?

Children's procedural counting skills are said to be guided by three whole-number counting principles (Gelman & Gallistel, 1978).

Children must learn how to count objects accurately through:

- developing a stable counting sequence (stable order)
- learning to use only one count term for each object (one-to-one correspondence), and
- knowing that the last number counted is the number of objects in the set (cardinality).

A stable counting sequence for small numbers of objects is usually well-developed by the time children are about two years old (Fluck & Henderson, 1996) and children between two and four years rarely make one-to-one correspondence errors in their own counting of small sets (Gelman & Gallistel, 1978).

Preschoolers' understanding of cardinality – that the last number counted represents the quantity of the set – has been less frequently investigated. However, with increasing age, children tend to spontaneously emphasise and repeat the last word in a count sequence (e.g. 'one, two, three, four. Four!') (Cordes & Gelman, 2005). Such evidence for children's understanding of cardinality is, however, controversial, as many adults do not emphasise or repeat the last number counted. Another approach to exploring

children's understanding of cardinality is the 'give-a-number task' in which children are asked to give numbers of different sizes to a puppet. On this task, children aged below about two-and-a-half years will select numbers at random, showing they do not understand the concept of cardinality. Between about two-and-a-half and three years, children will reliably give one object and over subsequent months, will successfully develop the skills to give two, three and four objects. Numbers beyond the number successfully given will still be given at random until children develop understanding of the cardinality of larger numbers (Sarnecka & Carey, 2008).

Mastery of the counting sequence enables children to solve increasingly complex problems. Children with a well-developed sense of counting as a problem-solving tool may use counting to compare the size of two sets, count objects accurately without needing to physically touch the objects, use counting to solve simple addition and subtraction problems, and use more complex counting strategies such as counting on from the larger set (Purpura & Lonigan, 2013).

Gelman (2008) has argued strongly that counting principles guide the development of counting, so that children may not yet be competent counters but will show they understand when the principles are violated. Although the debate in this area is ongoing, there is reasonably strong evidence from the work of Gelman and colleagues (Gelman & Gallistel, 1978; Gelman & Meck, 1983) that children aged two-to-four years can detect when a puppet makes errors in one-to-one correspondence and cardinality, even for numbers they cannot yet count themselves. The central role of whole-number counting principles, Gelman (2002) argues, may underlie children's difficulties with fractions, because children's existing whole-number knowledge does not map directly onto developing understanding about rational numbers.

Mastery of the counting sequence enables children to solve increasingly complex problems.

What other informal reasoning is there about number concepts?

Even before children develop proficiency in counting, there is evidence of informal reasoning about a range of other number concepts.

Two-year-olds show reasonable accuracy in identifying the larger of two sets of objects (e.g. three compared with four, three compared with five), although their counting skill is still not well developed (Brannon & Van de Walle, 2001). Such skills are not only evident for small numbers, with five-year-old children showing skills in estimating the greater of two large quantities (Barth et al., 2006). In this way, children show they are acquiring simple concepts of more and less, and that this understanding develops before they can use counting to compare numbers.

Another key development in preschool children's number sense occurs when they understand when two sets of objects have the same number (i.e. equivalence). Some researchers argue that preschoolers develop simple equivalence concepts before they are competent counters (Mix, 1999; Mix, Huttenlocher, & Levine, 1996). For example, initially children understand numerical equivalence only when the two sets are similar (e.g. black dots), but later they develop skills in detecting equivalence between dissimilar sets (e.g. dots and sounds). These more complex skills become evident only once children become proficient in counting.

Children also engage in sharing behaviour, or one-to-one dealing, which is a strategy for determining equal shares. Yet although children engage in this strategy proficiently, it is only with development that they understand that the procedure creates equal shares (Muldoon, Lewis, & Towse, 2005).

Connections between preschoolers' numeracy skills and school achievement

Children enter school with a wide range of early numeracy skills but they vary greatly in how they acquire, and how quickly they acquire, different concepts (Klibanoff, Levine, Huttenlocher, Vasilyeva, & Hedges, 2006; Kroesbergen, Van Luit, Van Lieshout, Van Loosbroek, & Van de Rijt, 2009). Children's informal number sense when they enter school provides a foundation for their school mathematics achievement and strongly predicts their mathematics competence later in school (Geary, 2015).

Several recent longitudinal studies have investigated mathematical development in the transition from preschool to the early years of primary school. For instance, in one study, counting skills and understanding of quantities and the relationships between them in the year before starting primary school predicted children's mathematics achievement and teacher ratings of competence in mathematics one year later (Aunio & Niemivirta, 2010). Other studies have demonstrated that, on entry to school, number sense measures and numeracy knowledge predict mathematics achievement in later school years (Aubrey, Godfrey, & Dahl, 2006).

Infants' basic capacities have also been shown to predict the number sense skills of preschoolers. Infants who showed a greater capacity to detect changes in number at the age of six months had higher maths achievement – including counting, number comparison, knowledge of number words and basic calculation – at three-and-a-half years (Starr, Libertus, & Brannon, 2013). These findings suggest some continuity in the development of mathematics skills from infancy, with more complex mathematical ideas building on earlier representations.

What affects mathematical skill development?

Research illustrating the link between mathematics skills in infancy and preschool does not suggest that mathematics development is fixed, as a range of additional factors can promote and enhance mathematics achievement. For example, self-regulatory behaviour has been shown to be a significant predictor of the acquisition of academic skills, including early numeracy. The development of self-regulation includes both behavioural and emotional regulation and involves controlling, directing and planning (McClelland et al., 2007). A longitudinal study investigated the relationship of behavioural regulation – comprising attention, working memory and inhibitory control – to literacy and numeracy achievement among three- and four-year-old children (McClelland et al., 2007). This study found that children with higher behaviour regulation exhibited higher achievement in early numeracy at two points in the year, even after taking into account children's gender, age and the language in which the tasks

were administered. Moreover, the children who exhibited faster growth in behaviour regulation over the year had more simultaneous growth in numeracy skills. Such findings indicate a relationship between these aspects of early cognitive development and early numeracy, but do not indicate that growth in behaviour regulation causes improvements in early numeracy.

Other research has suggested that working memory may underlie mathematics achievement. In a small longitudinal study, researchers assessed working memory at the start of the first year at school, mathematics achievement four months later, and again at the beginning of the second year at school (De Smedt et al., 2009). Children's achievement in mathematics early in the first year of school was the strongest predictor of achievement at the beginning of their second year of school. However, children's ability to retain information in short-term memory (as measured by their recall of non-words and their digit span) also predicted their mathematics achievement, even after taking prior achievement into account.

There is also good evidence that early literacy and numeracy development are related (Purpura & Napoli, 2015). One study with 180 preschool children showed that children with better language skills tended to have better informal numeracy, which in turn led to improved numeral knowledge (Purpura & Napoli, 2015). Thus, language skills do not affect numeral knowledge directly; rather the effect of language is indirect, through improved informal numeracy. Informal numeracy has a direct relationship to numeral knowledge, but informal numeracy also influences the development of print knowledge, which in turn is related to numeral knowledge.

The relationship between early numeracy, literacy development and formal mathematical knowledge among children in preschool and the early years of school is clearly complex.

The relationship between early numeracy, literacy development and formal mathematical knowledge among children in preschool and the early years of school is clearly complex. Both literacy and numeracy skills may predict early maths achievement, but the relationships may depend on the form of the skill, with literacy skills less predictive of non-linguistic maths tasks (LeFevre et al., 2010).

Concluding thoughts

Early numeracy skills develop significantly before children are exposed to formal teaching. Research from neuroscience and psychology has been enormously influential in establishing infants' early sensitivity to number concepts. Such research, which began in the field of psychology, suggested that infants process numbers, at a very basic level, well before they develop oral language. More recent neuroscience research investigated these claims from a different perspective, and suggested unique brain activity corresponding to changes in number, or in response to incorrect calculations. Moreover, research in psychology and education describes the development of early numeracy, and suggests that skills in infancy and preschool are related to children's early success in school mathematics. In conjunction, this research highlights the very significant role of early numeracy development for young children.

Given that early numeracy skills predict achievement in mathematics as children progress through school, interest has developed in trying to identify predictors of variation in numeracy growth, particularly as preschoolers already show wide variation in numeracy skills. This implies that school teachers will encounter children with a wide range of early numeracy skills even at school entry. Already in preschool learning environments, teachers can vary significantly in the amount of mathematical information they convey while interacting with children. Such variation is related to the growth in numeracy skills over a year, with greater growth in numeracy skills related to greater maths-specific talk among teachers (Klibanoff et al., 2006). Fostering understanding of early numeracy development among preschool educators is an important step towards developing early learning contexts that support children to develop mathematical thinking. Preschool teachers could be trained in the explicit use of

'maths talk' in their everyday interactions with children to enhance opportunities for children to develop their early numeracy skills.

Research strongly suggests that early numeracy development can be supported by interactions between young children, family members and early childhood educators. Parents positively influence their preschool child's maths achievement when they engage in direct (e.g. teaching their children the number words and counting) and indirect (e.g. integrating numeracy into everyday tasks such as cooking) numeracy practices with their child at home (LeFevre et al., 2009). Yet, everyday practices that can support numeracy development are reported far less commonly than practices that support literacy development (Anders et al., 2012). One approach to fostering numeracy practices is through increasing the knowledge of early childhood educators about what young children understand about numeracy, how growth occurs and how educators can promote understanding.

This review has described the very early development of numeracy skills among preschool children, drawing on research from neuroscience, psychology and education. Early numeracy knowledge develops spontaneously in everyday contexts. It may initially be fragile and incomplete, but it can be fostered through interactions with caregivers to provide a solid foundation on which school mathematics teaching can build. Understanding more about preschoolers' early numeracy development is important in informing educational practices, understanding the variation in early numeracy skills among preschoolers, fostering early numeracy among children whose skills are less developed, and understanding why some children with well-developed early numeracy have difficulties learning mathematics at school.

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