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CHILDREN'S COGNITIVE DEVELOPMENT AND LEARNING

Usha Goswami

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We want this report to contribute to the debate about the future of primary education, so we would welcome readers' comments on anything it contains. Please write to: administrator@cprtrust.org.uk. The report contributes to the Trust's research review programme, which consists of specially-commissioned surveys of published research and other evidence relating to the Trust's eight priorities. This survey relates to priority 7, **pedagogy**:

> Develop a pedagogy of repertoire, rigour, evidence and principle, rather than mere compliance, with a particular emphasis on fostering the high quality classroom talk which children's development, learning and attainment require.

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CHILDREN'S COGNITIVE DEVELOPMENT AND LEARNING

Introduction

'At the heart of the educational process lies the child'. This observation from the Plowden Report (CACE 1967) remains as true at the time of writing in 2015 as it was in 1967. Since 1967, however, there has been an explosion of research on how children of primary age develop, think and learn. Some of this research contradicts basic conclusions from the Plowden Report. For example, it is no longer widely believed that there are different developmental stages in learning to think (Piaget's theory, CACE 1967: 50). Similarly, it is not believed that a child cannot be taught until she/he is cognitively 'ready' (CACE 1967: 75). Rather, it is important to assess how far a child can go under the guidance of a teacher (the 'zone of proximal development', Vygotsky 1978).

Given the enormous amount of empirical research into cognitive development since 1967, the survey provided in this report is necessarily selective. Fuller expositions can be found in Kuhn and Siegler (2006), Siegler *et al*. (2006), Slater and Quinn (2012), and Goswami (2002, 2008, 2014). Here, we use the notion of 'foundational developmental domains' to provide coherence across the field (Wellman and Gelman 1998). These foundational domains are naïve physics (knowledge about the physical world of objects and events), naïve biology (conceptual knowledge about the world of animates and inanimates) and naïve psychology (understanding and predicting people's behaviour on the basis of psychological causation). New research in cognitive developmental neuroscience is revealing powerful learning in all three domains from the earliest months of life (Johnson & de Haan, 2011). We focus here on key areas of consensus in the wider field, while highlighting current controversies (for example in research in mathematics learning). We concentrate on *experiments* investigating how children develop cognitively, particularly in terms of learning, thinking, and reasoning, and how social/emotional development sets the framework for the child's learning in the 'learning environments' created by their families, peers, schools and wider society.

1. Learning

The infant brain has a number of powerful learning mechanisms at its disposal, even prior to birth. The foetus can hear through the amniotic fluid during the third trimester, and memory for the mother's voice is developed while the baby is in the womb (DeCasper and Fifer 1980). Foetuses can also learn to recognise particular pieces of music (such as the theme tune of the soap opera *Neighbours*, Hepper 1988). These responses seem to be mediated by the brainstem (Joseph 2000). Cortical activity is also present within the womb. For example, there are functional hemispheric asymmetries in auditory evoked activity (Schluessner *et al*. 2004).

The majority of the brain cells (neurons) comprising the mature brain form before birth, by the seventh month of gestation (see Johnson & de Haan, 2011 for overview). This means that the environment within the womb can affect later cognition. For example, certain poisons (for example excessive alcohol) have irreversible effects on brain development. Alcohol appears to have a specific effect on later mathematical cognition, via its effects on the development of the parietal cortex (a brain structure active during spatial cognition, Kopera-Frye *et al*. 1996; and see Section 8 below, 'Cognitive prerequisites for reading and number').

1a. Statistical learning by neural networks

Recent research in visual and auditory learning has revealed that neural sensory *statistical learning* following birth is a crucial part of cognitive development. The brain learns the statistical structure of experienced events, building neural networks to represent this information using algorithms which have been discovered via research in machine learning (see Section 1e). Statistical learning is unconscious and continues throughout life (for example, it is one basis for developing stereotypes). Babies can distinguish simple visual forms (for example cross versus circle, Slater *et al*. 1983) from birth, and can map cross-modal correspondences (when the same stimulus is experienced in different modalities) from the first month (Meltzoff and Borton 1979; Spelke 1976). Even 3-month-olds can detect which of two videos of kicking feet shows *their own* kicking feet (contingency detection, see Gergely 2002). Babies also seem to categorise what they see, forming a generalised representation or *prototype* against which subsequently-presented stimuli are then compared. This is statistical learning. Carefully-controlled experiments showing babies cartoon figures or pictures of real animals demonstrate that the babies learn statistical patterns in the input, such as which features co-occur together (for example long legs and short necks, see Younger 1990). They learn about the features in different objects, and about the *interrelations* between different features, thereby learning correlational structure. Rosch (1978) has argued that humans divide the world into objects and categories on just such a correlational basis. Certain features in the world tend to co-occur, and this co-occurrence specifies natural categories such as trees, birds, flowers and dogs. Babies' brains apply the same statistical learning mechanisms to dynamic displays, learning *transitional probabilities* between which objects or events follow each other (for example Kirkham *et al*. 2002) and extracting *causal structure*.

The infant brain is equally skilled in the auditory domain. Perceptual cues to speech rhythm are even tracked from inside the womb later in gestation, and the brain tracks statistical dependencies and conditional probabilities between sound elements following birth. Auditory statistical learning is one basis of language acquisition. In language, we can think of prototypical sound elements, such as a prototypical 'P' sound, or a prototypical 'B' sound. Infant brains use auditory perceptual information about correlational structure to construct these prototypes (Kuhl 2004). The brain registers the acoustic features that regularly co-occur, and these relative distributional frequencies yield phonetic categories like 'p' and 'b'. Although the brain of the neonate can distinguish the phonetic categories comprising all human languages, by around one year of age the brain has specialised in discriminating the phonetic categories used in the native language/s (Werker and Tees 1984). During the first year, infants also learn the statistical patterns (transitional probabilities) that govern the sequences of sounds used to make words in their language/s (Saffran *et al*. 1996). This statistical learning occurs in the context of communicative interactions with caretakers. Babies will not learn language from watching television, even if the 'input' is equalised to that offered by live caretakers (Kuhl *et al*. 2003). This is because social interaction plays a critical role in perceptual learning, as discussed later.

1b. Learning by imitation

Another important form of learning present from birth is learning by imitation. Meltzoff and Moore (1983) showed that babies as young as one hour old could imitate gestures like tongue protrusion and mouth opening after watching an adult produce the same gestures. By around 9 months, babies can learn how to manipulate novel objects such as experimenter-built toys by watching others manipulate them (Meltzoff 1988). Older babies can even imitate intended acts when the adult demonstrator has an 'accident'. For example, when an adult intends to insert a string of beads into a cylindrical container but misses the opening, the infant takes the beads and puts them in successfully (Meltzoff 1995). This shows that the babies attribute *goals and intentions* to the actor. Understanding the goals of another person transforms their bodily motions into purposive behaviour (Gergely *et al*. 2010).

1c. Learning by analogy

Learning by analogy is another important form of learning that is present early in life. Analogies involve noticing similarities between one situation and another, or between one problem and another. This similarity then becomes a basis for applying analogous solutions. Infants' ability to learn by analogy can be tested using simple problem-solving procedures. For example, an attractive toy might be out of their reach and behind a barrier (such as a box), with a string attached to the toy lying on a cloth (Chen *et al*. 1997). To get the toy, the infants need to remove the barrier, pull on the cloth to bring the string within reach, and then pull the string to get the toy. By presenting different problem scenarios with the common features of cloths, boxes and strings, Chen *et al*. demonstrated that 13-month-olds could use analogies to solve these problems. Toddlers can solve similar analogies in more complicated situations (Brown 1990) and, by the age of 3, children can solve formal analogies of the kind given in IQ tests (Goswami and Brown 1989). However, successful analogising depends on familiarity with the relations underlying the analogy. The multiple choice IQ test-type analogies given to 3-year-olds involved familiar causal relations (as in 'chocolate is to melting chocolate as snowman is to puddle'), in preference to more unfamiliar or abstract examples.

1d. Causal learning

Finally, causal or 'explanation-based' learning is also present in infancy. 'Explanation-based learning' is a concept drawn from research on machine learning. It depends on the machine's ability to construct causal explanations for phenomena on the basis of specific training examples. If the machine can explain to itself why the training example is an instantiation of a concept that is being learned, learning is rapid. Baillargeon *et al*. (2009) have argued that infants are faced with similar problems in learning about the physical world. For example, they see a variety of instantiations of a particular phenomenon, such as objects *falling*, and need to work out what causes them to fall. In a series of experiments, Baillargeon showed explanation-based learning at work in infants' physical reasoning about containment, support, occlusion and other events. The infants could also make predictions about novel events, demonstrating causal rather than associative learning. For example, they could work out which cover should conceal a tall object. The specific training examples that they received changed the age at which this ability emerged (these are described as 'teaching experiments'; see Wang and Baillargeon 2008).

1e. Connectionist models of learning and cognitive neuroscience data

All forms of learning important for human cognition are thus present in rudimentary form soon after birth. Statistical learning, learning by imitation, learning by analogy and causal learning underpin cognitive development. Developmental cognitive neuroscience is revealing how powerful these learning mechanisms are, for example in rapid learning about social stimuli (like faces, Farroni *et al*. 2002), physical events (like grasping actions, Tai *et al*. 2004), and language (Dehaene-Lambertz *et al*. 2006). *Connectionism* is the computational modelling of learning via 'neural networks'. Each unit in the network has an output that is a simple numerical function of its inputs. Cognitive entities such as concepts or aspects of language are represented by patterns of activation across many units, just as cognitive representations are distributed in the brain. Connectionism has achieved some important *in principle* demonstrations of what simple networks can learn using statistical algorithms. For example, networks are very efficient at learning underlying structure (such as linguistic structure, conceptual structure). By recording statistical associations between features of the input, complex structure such as grammar can be learned without assuming innate knowledge (such as pre-knowledge about language via an innate 'Language Acquisition Device', see Section 4 following – 'Language'). Prior to connectionism, most cognitive theories assumed symbolic representations (the 'algebraic' mind, see Elman 2005). This is no longer the case. Modern cognitive neuroscience conceptualises the entire cognitive system as a 'loose-knit, distributed representational economy' (Clark 2006). There is no all-knowing, inner homunculus or 'central executive' that governs what is 'known' and that orchestrates development. Rather, there is a 'vast parallel coalition of more-or-less influential forces whose ... unfolding makes each of us the thinking beings that we are' (page 373).

1f. Neural structures and mechanisms and multi-sensory distributed representations

An important issue for education is whether the young child's brain has basically the *same* structures (localised neural networks) as the adult brain, and whether these structures carry out the same *functions* via the same *mechanisms*, or whether the child's brain is differently-organised. If child and adult neural structure and function were more similar than different, then development would consist largely of *enrichment*. Experiences in the child's learning environments would amplify existing connections between structures and create new connections, thereby developing novel pathways or functions via learning. Education would be the most critical learning environment supporting cognitive enrichment, as most children arguably experience a larger diversity of experiences at school than at home. To date, neural studies of language processing by infants, of face processing, of working memory and of the behaviour of "mirror neurons" (see section 2d following) suggest that the child's brain has essentially the same structures as the adult's brain, which perform the same functions via the same mechanisms. Hence cognitive development is largely a matter of neural enrichment. The learning environments of home, school and the wider culture enable experience-dependent learning, and lay the basis for the cognitive and emotional functioning of the adult system.

Implications for education

The brain will learn from every experienced event (neuroplasticity). However, cognitive representations are distributed and *cumulative learning* is crucial for education. There will be stronger neural representation of what is common across experience ('prototypical') and weaker representation of what differs. It may be that direct teaching of what is intended to be prototypical (for example reminding of the general principles being taught via specific examples) will strengthen learning. The brain will record multiple representations of experience (for example, generating experience-dependent connections in motor cortex and in sensory cortices). This supports the benefits of multi-sensory approaches to education, but it does not support the idea that unisensory teaching approaches will have special benefits (for example visual, auditory *or* kinaesthetic approaches). Learning depends on neural networks distributed across multiple brain regions: visual, auditory *and* kinaesthetic. Cognitive representations will be graded in terms of (for example) the number of relevant neurons firing, their firing rates, and the coherence of the firing patterns (Munakata 2001). This can lead to apparent 'gaps' in learning, when a network is not yet strong enough to support generalisation to every relevant context.

Connectionism has shown that a constant learning mechanism can yield learning effects previously considered developmentally special. Cumulative experience acting on simple mechanisms (eg tracking conditional probabilities) yields apparent 'critical periods' for learning (when a developmental time window appears particularly effective), 'U-shaped' learning curves (apparent mastery, then loss of a skill, followed by regaining mastery), and a 'novice' system that is very responsive to learning from errors followed by an 'expert' system which is more entrenched and resistant to error-based feedback. The frequency with which learning events are experienced and the quality of the 'learning enviroment' are therefore crucial to the acquisition of expertise. Motivation to learn is also important, as the emotional system can modulate sensory processing for example via attentional processes.

Connectionist models demonstrate that complex cognition can arise without assuming symbolic thought. However, as Vygotsky made clear (see Section 9 following – 'Theories of cognitive development and intelligence'), part of the input for human cognitive development is internal and symbolic. These internal mediators are also crucial for cognitive development; for example inner speech, the imagination, and pretend play.

2. Knowledge construction

Much of the knowledge that we think of as cognitive seems to develop initially via the way that our perceptual systems operate. For example, some types of motion typically specify mechanical agents (such as regular motion), and other types of motion typically specify biological agents (for example self-initiated, erratic motion). Dynamic inter-relations between objects perceived in the everyday world give the impression of causality. This perceptual analysis of the dynamic spatial and temporal behaviour of objects and agents appears to be one basis of knowledge construction by the infant and child.

2a. Naïve physics

Infants and young children learn about mechanical causality from perceptual information (for example Leslie 1994). Perception organises itself fairly rapidly around a core framework representing the arrangement of cohesive, solid, three-dimensional objects which are embedded in a series of mechanical relations such as *pushing*, *blocking* and *support*. Action is crucial to the development of these explanatory frameworks: as the child becomes able to manipulate different causes and observe the effects, further learning occurs. Causal principles such as temporal order, intervention in situations, and real world knowledge about likely causes and effects (for example that a switch is probably a cause of something) are all important for inferring the causal structure of physical events, and can already be observed in two- and three-year-olds (for example Bullock *et al*. 1982; Shultz 1982). Four-year-olds can use covariation data to induce causal structure (again, apparently using statistical learning algorithms, such as causal Bayes nets; Gopnik *et al*. 2001). Causal reasoning is well-developed early in childhood. However, the ability to deal effectively with multiple causal variables – scientific reasoning – develops more slowly.

Scientific reasoning is usually understood as the kind of thinking that requires the co-ordination and differentiation of theories and evidence, and the evaluation of hypotheses (for example Kuhn 1989). Research suggests that children as young as 6 understand the goal of testing a hypothesis, and can distinguish between conclusive and inconclusive tests of that hypothesis in simplified circumstances (for example Sodian *et al*. 1991). Young children are poorer at scientific reasoning in situations when they have to ignore their pre-existing knowledge and reason purely on the basis of the data, and when they have to keep multiple variables in mind at once (Kuhn *et al.* 1995). However, adults are poor at this too. There is a 'confirmation bias' in human reasoning – a tendency to seek out causal evidence that is consistent with one's prior beliefs. This is a major source of inferential error in fields as disparate as science, economics and the law, as well as affecting young children's thinking. Indeed, when younger children have *fewer* prior beliefs than adults, their reasoning can be *more* effective (Goswami, 2014). For example, 6-year-olds outperformed adults in statistical 'base rate' problems, such as deciding whether a pretty girl was likely to be trying out for a position as cheerleader or a position in the school band. The base rate information was that in a group of 30 girls, 10 wanted to be cheerleaders and 20 wanted to be in the school band. The children were more likely to correctly answer "the school band", because they were less influenced by stereotypical knowledge gained via experience (that cheerleaders tend to be pretty).

Naïve or intuitive physics, rooted in the perception of objects and events, in general yields reliable information about the structure and action of physical systems. However, in some cases naïve physics gives rise to misleading models of the physical causal structure of the world. For example, most children (and adults) employ a pre-Newtonian, 'impetus' theory of projectile motion (for example Viennot 1979). Each motion must have a cause, and so we think that if a ball is dropped from a moving train, it will fall downwards in a straight line. In fact, it will fall forwards in a parabolic arc (Kaiser *et al*. 1985), as the moving train imparts a force (Newtonian physics). Learning Newtonian physics requires direct instruction. Cognitive neuroscience studies suggest that when we learn non-intuitive scientific concepts, such as the Newtonian theory of motion, these concepts do not replace our misleading naïve theories. Rather than undergoing conceptual change, the brain appears to maintain *both* theories. Selection of the correct basis for reasoning in a given situation then depends on effective inhibition of incorrect information (via metacognitive strategies – see Section 6 following, 'Metacognition and executive function').

2b. Naïve biology

Watching moving objects that change in their speed or direction gives important information about animacy. Children learn that things that move on their own are animate agents, and that their movements are not predictable but are caused by their own internal states (for example Gelman and Opfer 2010). Biological entities can also grow taller or fatter, they can change their colour or form (for example caterpillar to butterfly), and they can inherit the characteristics of their forebears. Much of this naïve biological knowledge is present by age 3 to 4. Perceptual similarity is another critical source of information, and is usually a reliable indication that objects share core properties such as blood, bones, or cellulose. When perceptual information is not reliable, even 2-year-olds prioritise structural similarity (for example having bones) in categorising biological kinds. Via experience and observation, young children have learned that 'insides' are more important than 'outsides'. For artefacts, *function* is judged to be the most important shared feature (for example something can be 'a bag' as long as it can be used to carry other objects). Language helps young children to focus on structural and functional similarity, as consistency of labelling (for example 'bird' for robin *and* ostrich, 'animal' for cat *and* cow, 'plant' for tree *and* buttercup) denotes biological categories.

Again, children go beyond the perceptual learning of statistical information about shared features and so on, and construct causal explanatory frameworks concerning the structure and action of biological systems. Statistical co-occurrences (for example that feathers reliably co-occur with wings, with flight, and with light body weight) help the child to distinguish a category like 'bird'. But adults have a 'theory' about why these features go together, which involves causal relations. Adults believe that there is a degree of *causal necessity* in the co-variation of low body weight, feathers and wings in birds, as these features facilitate flight. Children seem to construct similar causal explanatory systems. Gelman (2004) describes this as an 'essentialist bias', arguing that young children have an early tendency to search for hidden, non-obvious features that make category members similar. Children's implicit assumptions about the structure of the biological world, and about the underlying nature of categories, again depend on their *experience* and the *quality* of their learning environments.

2c. Naïve psychology and 'theory of mind'

The causal explanatory framework that children generate to explain human behaviour has been called 'theory of mind' (ToM). Infants and young children develop understanding of psychological causality using the same learning mechanisms discussed earlier. They learn the correlations and conditional probabilities embedded in the human behaviour around them, for example the kinds of events that lead to happiness or to anger. They observe goal-directed actions and induce intentions, they observe emotional responses and induce causes, they follow the gaze of others and induce interest or intention, they engage in joint attention with caretakers, for example over shared toys and they learn social contingencies. This perceptually-based social-cognitive learning is then enriched via imitation, pretend play and language.

Developing a 'theory of mind' requires an understanding of the mental states of others, so that you can predict their behaviour on the basis of their beliefs and desires. Imitation and understanding others as being 'like me' is one source of knowledge about desires. For example, if another person is seen reaching for an object, the action can be imbued with goal-directedness because of the infant's own experiences with similar acts (Meltzoff 2010). The behaviour of others is also understood via pretend play. For example, socio-dramatic role-play helps children to gain insights into the beliefs, desires and intentions of other agents. Language is also important, as family discourse about emotions and their causes is linked to earlier development of ToM (for example Dunn *et al*. 1991). Conversations about psychological causality offer young children opportunities to enquire, argue and reflect about human behaviour (Hughes, 2011). Deaf children born to hearing parents show delays in acquiring ToM (Peterson and Siegal 1995). This appears to be due to the absence of pervasive family talk about abstract mental states, as deaf children born to *signing* deaf parents do not show ToM delays.

A dominant view in the literature was that a 'theory of mind' did not develop until a watershed in psychological understanding occurred at the age of around 4 years (for example Wimmer and Perner 1983). This view is no longer widely held. For example, even babies (around 12 months) expect people to *help others* and to behave *fairly*. These socio-moral expectations were revealed in clever experiments. For example, in one experiment two identical toy giraffes were sitting in view of the infant. As the infant watched, the experimenter showed the giraffes two toys (saying excitedly "I have toys!"). The giraffes began dancing, and shouting "yay, yay". The experimenter then either put *both* toys in front of one giraffe, or gave the giraffes one toy each. The babies looked significantly longer at the event which was unfair. Such experiments, which have various control conditions to rule out other explanations, suggest that some *socio-moral norms* may be innate and culturally universal. Early-emerging norms appear to include a concern for fairness, a preference for helping over hindering, and a distaste for actions that harm others. Clearly, these norms will be elaborated in different ways by different cultures and different family learning environments. The human brain is a social brain, because humans are a social species. Babies appear to be innately predisposed to be with other humans and to learn social and moral norms.

2d. Cognitive neuroscience: the mirror neuron system

Socio-moral cognition is currently an active area of research in developmental cognitive neuroscience. This is partly because of the discovery of a neural system called the 'mirror neuron system', which appears to be very important with respect to imitation and language. Mirror neurons were discovered in primate research examining how actions are represented in the brain, and how action, imitation and intention might be linked. Mirror neurons were found to activate when the monkey performed object-directed actions such as tearing, grasping, holding and manipulating, and the same neurons also fired when the animal observed someone else performing the same class of actions. Mirror neurons were even activated by the sound of an action, such as paper ripping or a stick being dropped

(Rizzolatti and Craighero 2004). Rizzolatti and colleagues pointed out that action recognition has a special status, as action implies a goal and an agent. Further, mirror neurons are only activated by biological actions (for example a human hand grasping), and not by mechanical actions (for example a robot grasping, Tai *et al.* 2004), even in infants. As the mirror neuron system is active when participants imitate the motor actions of another human, or imitate their facial expressions, it may be one neural substrate for ToM - understanding the actions and internal states of others. Other neural structures that are activated during ToM tasks by adults are also activated by infants (e.g., medial pre-frontal cortex [mPFC]). Children with autism have great difficulty in understanding the actions and internal states of others, and some suggest that atypical mPFC function could be used to identify these children during infancy. Crucially, however, all the cognitive neuroscience studies to date are documenting correlations and not causes. While new technologies in neural imaging are uncovering important links between brain development and behaviour, longitudinal imaging studies tracking what is cause and what is effect are currently lacking.

Implications for education

Cognitive development in the foundational domains of naïve physics, naïve biology and naïve psychology reflects the learning mechanisms discussed in Section 1 above, along with the active construction by the child of causal explanatory frameworks about the structure and action of systems. The idea that knowledge is actively constructed by the child is one of the central tenets of Piagetian theory. Piaget's related notion of stage-based change, that children think and reason in different ways according to their stage of cognitive development, has been undermined however. Nevertheless, his idea that action (physical interaction) with the world is a critical part of knowledge construction has been supported. The basis of cognition is indeed in sensory-motor learning, as Piaget proposed. However, sensory-motor representations are not *replaced* by symbolic ones. Rather, they are augmented by knowledge gained through action, language, pretend play and teaching.

3. Memory

Memory consists of a variety of cognitive systems. Chief among these are semantic memory (our generic, factual knowledge about the world), episodic memory (our ability consciously to retrieve autobiographical happenings from the past), implicit or procedural memory (such as habits and skills), and working memory (our short-term store). Memories that can be brought consciously and deliberately to mind (semantic and episodic memory) are called declarative, whereas knowledge that is usually indexed by changes in performance (for example riding a bicycle) is called implicit memory. Associative learning and habituation (ubiquitous mechanisms of learning across species, see Section 1 above) are also implicit or procedural. Visual recognition memory is well-developed in young children. For example, Brown and Scott (1971) showed children aged from 3 - 5 years a series of 100 pictures, and found recognition memory on 98 per cent of trials. Declarative episodic memories develop more slowly. Children (and adults) *construct* declarative memories, and therefore prior knowledge and personal interpretation affect what is remembered.

3a. The development of episodic memory

Remembering is embedded in larger social and cognitive activities, and therefore the knowledge structures that young children bring to their experiences are a critical factor in explaining memory development and learning. Temporal and causal structures are particularly important. Very young children may not structure their experience in memorable ways, particularly if they do not understand particular experiences (for example being abused), or if they do not have a clear temporal framework for organising the experience. Nevertheless, when tested with simple scenarios (for example 'giving teddy a bath'), even 18-month-olds retain memories that display temporal ordering and are arranged around a goal (Bauer 2010). Early event memory is not composed of a series of disorganised snapshots of individual components of the event. Nelson (1986) showed that younger children concentrate on remembering routines, as routine makes the world a predictable place. However, very young children also remember distinctive events. In one longitudinal study, Fivush and Hamond (1990) reported a 4-year-old who recalled that, when he was 2½, 'I fed my fish too much food and then it died and my mum dumped him in the toilet'. Young children rarely invent memories that have not occurred (Gilstrap and Ceci 2005). Intensive research on young children's eyewitness testimony shows that younger children are more susceptible to 'leading questions', but these increase inaccurate acquiescence (the child agrees that something happened which did not). Leading questions rarely cause children to invent false memories. Even pre-schoolers (3 – 5 year olds) make relatively few errors in response to misleading questions about abuse (16 per cent errors, see Eisen *et al.* 2002, who studied maltreated and abused children from low socio-economic status (SES) families).

The ways in which parents and teachers interact with children influences the development of episodic memory. Parents or carers who have an 'elaborative' conversational style have children with more organised and detailed memories (Reese *et al.* 1993). An elaborative style involves amplifying the information recalled by the child and then evaluating it. Mothers who tend to switch topics and provide less narrative structure, and who seldom use elaboration and evaluation, have children who recall less about the past. Longitudinal studies have shown that it is the experience of verbalising events *at the time that they occur* that is critical for long-term retention (Fivush and Schwarzmueller 1998). Language enables children to construct extended, temporally-organised representations of experienced events that are narratively coherent. Partaking in elaborative conversation facilitates the construction of a personal history.

3b. Working memory

The memory system for short-term recall is usually called working memory. Working memory (WM) is a limited capacity 'workspace' that maintains information temporarily while it is processed for use in other cognitive tasks, such as reasoning, comprehension and learning (for example Baddeley and Hitch 1974). Working memory capacity increases as children get older, tending to plateau during the teenage years. Although there are both visual and phonological (sound-based) WM systems, most developmental research has focussed on the phonological system, as even visually-presented material is often translated into speech-based codes for short-term retention (eg telephone numbers). The amount of material that can be stored temporarily in this speech-based system increases with age. The capacity of the phonological WM system is also affected by factors like word length (more words are retained if they are short), phonological confusability (it is more difficult to retain words that sound similar, such as "hat, rat, tap, mat"), and speech rate (children who articulate more slowly retain less information). The developmental causes of poor working memory are currently not well-understood. For example, the quality of social and intellectual learning environments at home do not seem to relate to individual differences in WM. The development of working memory is important for the development of metacognition and the development of reading (see Sections 6 and 8, following).

Implications for education

Even young children have remarkably good semantic and episodic memories. Children's memories for their own experiences are better when a carer or teacher adopts an elaborative conversational style to help them to make sense of temporal and causal aspects of their experiences. Adapting our dialogue with young children leads to more organised and detailed learning and memory. These findings suggest that using elaboration in classroom dialogues will aid retention and understanding. Children's autobiographical memories tend to be accurate, even for unusual events, and the invention of 'false memories' is rare. Having a poor working memory can cause poor academic progress. Children with poor WMs will struggle to remember the teacher's instructions, and will forget where they are in a piece of work, perhaps continually losing their place. Cognitive neuroscience research is currently focused on adults and on which brain structures are important for different types of memory. For example, the hippocampus is known to play a key role in consolidating memories and in recollection. Developmental aspects are not well-understood. For example, children with early hippocampal damage can acquire normal semantic memories and show age-appropriate WM, while having enormous difficulty in remembering the events of their daily lives (Vargha-Khadem *et al*. 1997).

4. Language

It is already clear that language plays a key role in cognitive development. Language aids conceptual development (Section 2b), the development of a theory of mind (2c), episodic memory development (3a) and is the basis of working memory (3b). It also plays a key role in Vygotsky's theory of cognitive development (see Section 9, following). Infants then use the same abilities to acquire the phonological (sound-based) aspects of language that they use to acquire knowledge about the physical and psychological worlds, namely associative learning, tracking statistical dependencies, tracking conditional probabilities and making analogies (see 1a). Word learning is aided by the universal tendency of adults (and children) to talk to babies using a special prosodic register called infant-directed speech (IDS) or 'Motherese'. IDS uses higher pitch and exaggerated intonation (for example increased duration and stress) to highlight novel information, which appears perceptually effective in facilitating learning (for example Fernald and Mazzie 1991). Children who are less sensitive to the auditory cues of the prosodic and rhythmic patterning in language may be at risk for developmental dyslexia and specific language impairment (for example Corriveau *et al*. 2007). Active production is also important for language acquisition, and babbling reflects early production of the structured rhythmic and temporal patterns of language and protosyllables. Deaf babies do not show typical vocal babble, however babies born to signing deaf parents will 'sign babble' with their hands, duplicating the rhythmic timing and stress patterning of hand shapes in natural sign languages (Pettito *et al*. 2004).

4a. Vocabulary development

The primary function of language is communication, and words are part of meaning-making experiences from very early in development. As discussed in Section 2, conceptual representations precede language development, being rooted in the perceptual experience of objects and events. Nevertheless, carers talk to babies before they can talk back, naming objects that are being attended to, commenting on joint activities or discussing the child's behaviour or apparent feelings. One study showed that toddlers hear an estimated 5000 – 7000 utterances a day, with around a third of these utterances being questions (Cameron-Faulkner *et al.* 2003). In a U.S. study, Hart and Risley (1995) estimated that children from high socio-economic status (SES) families heard around 487 utterances per hour, compared to 178 utterances per hour for children from families on welfare. Hence by the time they were aged 4 years, the high SES children had been exposed to around 44 million utterances, compared to 12 million utterances for the lower SES children. Word learning is also important for cognitive development because it is symbolic. Words are symbols because they *refer* to an object or to an event, but they are not the object or the event itself. Symbols allow children to disconnect themselves from the immediate situation. Gestures are also symbolic (for example waving 'goodbye'). Gesture precedes language production in development, providing a 'cognitive bridge' between comprehension and production (Volterra and Erting 1990). Action is used to express meaning. Even later in cognitive development, gesture can provide important information about what the child understands in a given cognitive domain. These (frequently) unconscious gestures are sensed by their teachers, who alter their teaching input accordingly (for example Goldin-Meadow and Wagner 2005). Gesture-speech 'mismatches' are often found when children are on the verge of making progress on a particular cognitive task.

Word learning (vocabulary development) is exponential in early childhood. Using the child language checklist (now translated into over 20 languages), Fenson *et al*. (1994) showed that median English spoken vocabulary size is 55 words by 16 months of age, 225 words by 23 months, 573 words by 30 months, and 6000 words by age 6. Comprehension vocabulary at age 6 is around 14,000 words (Dollaghan 1994). However, the developmental range can be enormous. For example, at 2 years, the range in word production is from 0 words to more than 500 words. Fenson *et al*. also showed that there was no 'burst' in vocabulary acquisition at around 18 months for most children. The 'naming burst' had been important theoretically, as it suggested the sudden cognitive achievement of the 'insight' that words can name (Bloom 1973). This achievement at 18 months appeared to fit neatly with Piaget's theoretical view (now discounted, see Section 2a) that a symbolic understanding of the 'object concept' developed at the same time. However, infants as young as 4 months seem to have worked out that words can name. They already recognise their own names, and the word for 'mummy' (Mandel *et al*. 1995). New word learning is extremely rapid, with around 10 new words acquired daily at age 2. This rapid learning has been called 'fast mapping' (Carey 1978). Although first conceived as a dedicated language-learning mechanism, fast mapping is a powerful form of exclusion learning which is not special to humans (for example, intelligent dogs can use 'fast mapping' to learn novel words; Kaminski *et al.* 2004). Children use a combination of the context in which new words are encountered and their position in a sentence to eliminate potential candidates regarding word meaning.

4b. Grammatical development

The set of grammatical 'rules' that determine how words can be combined into sentences and phrases is called syntax. Morphology refers to the 'rules' governing the internal structure of words – we can say 'I'll undo it' but not 'I'll unmake it'. Whether grammatical development is a matter of acquiring rules or of reproducing pieces of heard language is the subject of intense debate. Rule-based views can be characterised by Chomsky's (1957) notion of a 'language acquisition device'; a specialised neural structure providing innate knowledge about the general rules that all languages obey along with knowledge of permitted variations. Tomasello (2000, 2006) has suggested that grammatical development depends on the learning environment rather than on a pre-determined neural system. Babies acquire particular constructions that are good grammatical forms piecemeal, they do not acquire general syntactic categories. Learning relies on what is being said around them. Children acquire 'utterances' that represent a single relatively coherent communicative intention. Children then build upon these piecemeal utterances by using the same pattern-finding mechanisms that underpin learning in other areas (statistical learning, categorisation, induction, analogy). Although it was previously believed that overt correction of grammatical errors by caretakers was rare, more recent research shows that extensive feedback is provided. However, adults *reformulate* the child's utterance as part of natural conversation rather than overtly correcting it (Chouinard and Clark 2003). Again, we see the important role of conversation in language learning (see also Section 1a).

Implications for education

Language development is critical to cognitive development, and shows marked variation in the preschool years. Both quality (use of IDS) and quantity (having natural conversations with children) are developmentally important. Children enter school with widely differing language experience and vocabularies, depending on the learning environments experienced at home and in nursery. Language and conversation may be an important focus in the reception class. Gesture can also be an important aspect of communication in the classroom. Sometimes children can reveal more knowledge via gesture than language. Both gesture and language are symbolic, enabling children to detach themselves from the immediate situation. This is important for enabling cognition itself to become the object of thought and reflection – metacognition (see Section 6).

5. Pretend play and the imagination

Pretend play may be the earliest manifestation of a child's developing ability to characterise their own cognitive relation to knowledge. Action (pretending) is another way to detach oneself from the immediate situation. In a famous paper, Leslie (1987) showed that in order to pretend that (for example) a banana is a telephone, the child must separate the *primary* representation of the banana (given by the sensory systems: yellow object with particular texture and smell) from the pretend representation (telephone receiver). The primary representation is the direct representation of the object, and it is crucial for cognition that our primary representations are veridical. During pretend play, this primary representation must be detached or 'quarantined' from the pretend representation of a telephone receiver. The pretend representation is not a representation of the objective world, rather it is a representation of a representation from that world. It is a *meta*representation. Thus the emergence of pretend play marks the beginning of a capacity to understand cognition itself – to understand thoughts as entities.

5a. The development of pretend play

Pretending develops during the second year of life, with early pretence typically tied to the veridical actions that people make on objects (for example a 12-month-old 'drinking' from an empty cup) and later pretence being more detached from object identities (for example a 2-year-old pretending a stick is a horse). Pretend play is usually carried out with others. Children show more advanced pretending when they imitate the pretence of others, and adult scaffolding of pretend play facilitates symbolic development (Bigelow *et al.* 2004). Language is also important, as social partners can use language to help to explain pretend situations, or can use "silly voices" to signal that a situation is pretend.

Pretend play is also linked to the development of a 'theory of mind' (ToM). However, different social partners offer different types of pretend play. Pretend play with siblings or friends differs from pretend play with the mother, and is more likely to be social pretence, because other children are usually in the drama themselves. Jenkins and Astington (1996) showed that children with siblings showed earlier ToM development than children without siblings, and that having siblings had stronger effects for children with lower language abilities. One reason that pretend play with siblings and friends helps to develop psychological understanding is that shared pretend play makes high demands for imaginary and co-operative interaction. Shared socio-dramatic play provides a large number of opportunities for reflecting upon one's own and others' desires, beliefs and emotions – sharing mental states. As children get older less time is spent in actual play, and more and more time is spent in negotiating the plot and each other's roles (Lillard 2002). This discourse about mental states enhances mind-reading skills. Hughes and Dunn (1998) showed in a longitudinal study of 4-year-olds that the rate of mental state talk between friends at nursery was significantly related to later performance on false belief and emotion understanding tasks. Mental state talk was also more advanced and more frequent in pairs of girls than in pairs of boys (see also Hughes, 2011).

There are also large individual differences in pretending. Dunn and Cutting (1999) showed that some children share an imaginary world together with great skill and enjoyment, while others prefer to engage in boisterous games or even engage in 'shared deviance' (for example killing flies together). Between 20% and 50% of preschool children invent "imaginary friends". Children who invent imaginary friends tend to have richer language skills than other children and tend to be better at constructing narratives. However, greater skill in mind-reading does not always go with better prosocial behaviour. A study of 7- to 10-year-olds found that those who bullied others showed advanced performance in theory of mind tasks (for example Sutton *et al*. 1999). It is unclear whether having advanced mind-reading skills enables a child to become a bully, or whether the experience of bullying *itself* aids children's social cognitive development.

5b. The role of the imagination in cognitive development

While Western psychology has focussed on the important role of imaginative play in enabling a deeper understanding of mind (social cognitive development), Russian psychology has emphasised effects on cognitive self-regulation (executive function, see 6). Vygotsky (1978) argued that the imagination represented a specifically human form of cognitive activity. According to his theory, a central developmental function of pretend play was that children had to act against their immediate impulses and follow the 'rules of the game'. This was thought to help them to gain control over their thoughts and actions, so that inappropriate responses could be inhibited. The child's playmates exert an important regulatory function as well. For example, Karpov (2005) reports a study of children aged from 3 to 7 years who were required to stand motionless for as long as they could. The play context was 'being a sentry'. When the children had to stand motionless alone in a room without a play context, they were significantly less successful compared to the play context. However, when they had to be a sentry in a room full of their playmates, they were most successful. The playmates were monitoring the sentry, helping him/her to stand still for longer. Russian neo-Vygotskians argue that adult mediation is required to initiate or extend socio-dramatic play for learning purposes, so that it becomes 'a micro-world of active experiencing of social roles and relationships' (Karpov 2005: 140). Vygotsky regarded play as a major factor in cognitive development.

Implications for education

Pretend play is an early form of symbolic activity. In symbolic play, the meaning of things to the child depends not on their status as real objects in the perceptual world, but on their status in the imaginary world. Through pretend play, the child is manipulating her cognitive relations to information, and taking a representation as the object of cognition (forming 'metarepresentations'). This is important for cognitive development. For example, the ability to reflect on and index one's own mental representations, tagging their internal source so that both current reality and past reality are kept in mind together, is metacognition (see Section 6). Pretend play with others is typically socio-dramatic play, and this is important for developing psychological understanding (ToM and mind-reading skills, Section 2c). The kind of language involved (mental state discourse) also provides a medium for reflecting on and knowing about our own thoughts and those of others. Pretending with others seems important for developing cognitive self-regulation skills (executive function). Both language and imaginative pretend play share the core developmental functions of enabling children to reflect upon and regulate their own cognitive behaviour, and to reflect upon and gain an understanding of the mind. Language and pretending are both symbolic tools for understanding the external world.

6. Metacognition and executive function

Metacognition is knowledge about cognition, encompassing factors such as knowing about your own information-processing skills, monitoring your own cognitive performance, and knowing about the demands made by different kinds of cognitive tasks. Executive function refers to gaining strategic control over your own mental processes, inhibiting certain thoughts or actions, and developing conscious control over your thoughts, feelings and behaviour. The assumption is that as children gain metaknowledge about their mental processes, their strategic control also improves. Developments in metacognition and executive function tend to be associated with language development, the development of working memory (which enables multiple perspectives to be held in mind) and nonverbal ability (Hughes 1998).

6a. The development of metamemory

Research in metacognition began with research on metamemory. Researchers studied children's awareness of themselves as memorisers, for example their awareness of their strengths and weaknesses in remembering certain types of information. In general, children turned out to be quite good at monitoring their memories. They did not differ markedly from adults on measures like judging how well they had learned something (both groups tend to be over-optimistic about their learning). However, younger children were less good at planning, directing and evaluating their memory behaviour (see Schneider and Lockl 2002). For example, they were not very good at deciding how much study time to allocate to particular memory tasks. Younger children also had more difficulty in keeping track of the sources of their memories than older children. As metamemory skills develop, memory performance is enhanced (for example, children become increasingly skilled at applying appropriate mnemonic strategies). Schneider *et al.* (2000) suggested that developments in self-regulation (executive function) rather than in self-monitoring might explain developments in metamemory in children.

6b. The development of inhibitory control

The term executive function derives from the 'executive deficits' that are exhibited by patients who have damage to the brain's frontal cortex. For example, when sorting a pack of cards according to a particular rule (say, by colour), frontal patients find it difficult to switch strategies when the sorting rule is changed (say, to shape). However, the patient is aware that 'this is wrong, and this is wrong, and this is wrong…' (Diamond 1990). Cognitive neuroscience studies show that frontal cortex is especially active during studies of working memory, of strategic control over behaviour and of the inhibition of inappropriate behaviours. The frontal cortex continues to develop during adolescence and early adulthood. In the last 2 decades, there has been an explosion of developmental research into inhibitory control and cognitive flexibility and links to frontal cortex (for example Diamond, 2013). Three- to 4-year-old children have considerable difficulty in rule shifting tasks, just like frontal patients, despite being able to verbally report new sorting rules (for example Zelazo *et al.* 1996). If asked to re-label the cards verbally before sorting them, however, even 3-year-olds can sort correctly after the rule has been switched (Kirkham *et al.* 2003). This suggests that younger children have difficulty in flexibly shifting their attentional focus, but can be helped to overcome these difficulties via language and instruction.

In general, two types of tasks have been used to measure inhibitory control in young children (Carlson and Moses 2001). One requires children to delay gratification of a desire, for example by suppressing a 'prepotent' response such as peeking at a gift. The second requires children to respond in a way that conflicts with a more salient response, for example by labelling pictures of the sun 'night' and pictures of the moon 'day'. Performance in both types of inhibitory control task improves with age. When gender differences are found, girls outperform boys at all ages (for example Kochanska *et al*. 1996). Hughes (1998) devised tasks to distinguish between inhibitory control, working memory and attentional flexibility. She found that all aspects of executive function developed together in preschoolers. Inhibitory control tasks are hence thought to tap a common underlying construct, with delay and conflict as key aspects. Planning is another important aspect of executive function, which also develops. Efficient planning and efficient inhibitory control are required for effective self-regulation. Performance in executive function tasks also correlates highly with performance in theory of mind tasks (for example Carlson *et al*. 2004). This is not surprising, as one set of tasks measures what the child knows about his or her own mind, and the other what the child knows about somebody else's mind (Schneider and Lockl 2002).

6c. Cognitive neuroscience studies

The classic view of the development of metacognition and executive function is that development is related to maturational changes in frontal cortex (Diamond, 2013). Brain imaging studies to date confirm significant correlations between structural developments in the brain and improved executive function, but the direction of cause and effect is unclear. Performance by children in conflict tasks such as the day/night task leads to strong activity in both dorsolateral and ventrolateral prefrontal cortex (for example Durston *et al*. 2002). Response inhibition tasks also lead to strong activation in dorsolateral prefrontal cortex (for example Luna *et al*. 2001). In the adult literature, researchers distinguish between 'cool' and 'hot' executive function. The former refers to making purely cognitive decisions (for example naming ink colour), whereas the latter involves making decisions about events that have emotionally significant consequences (for example, when gambling). 'Hot' executive function activates orbitofrontal cortex in adults. From experimental studies, Kerr and Zelazo (2004) argued that 'hot' executive function develops in a similar way to 'cool' executive function in young children. The key factor developmentally appears to be managing conflicting representations.

Implications for education

Metacognition and executive function both show important developments in the primary years. As discussed in Sections 1, 2 and 3, learning, knowledge construction and memory operate in similar ways in young children and adults. Self-regulation and inhibitory control do not. Gaining reflective awareness of one's own cognition and how to regulate it is a major achievement of the primary years. Executive function abilities have important links to success in school. For example, children with attentional disorders are poor at exerting inhibitory control and tend to be impulsive and disruptive in class. Children with anti-social behaviour disorders also lack inhibitory control, and this can be accompanied by poor language skills. Poor language skills make the child less effective at controlling his or her thoughts, emotions and actions via inner speech. Learning in classrooms can be enhanced by developing self-reflection and inhibitory control in young children, for example via guided play and conversations about transgressions. Children with good metacognitive skills can improve their own learning and memory, for example by adopting effective cognitive strategies and by being aware of when they don't understand something and seeking more guidance. This has been shown most clearly by metamemory research. It is also demonstrated by studies on 'learning to learn', which are reviewed in Section 7.

7. Inductive and deductive reasoning

Contrary to what was believed at the time of the Plowden Report in 1967, inductive and deductive reasoning are available early in development and function in highly similar ways in children and in adults. Children do not gradually become efficient all-purpose learning machines, acquiring and applying general reasoning strategies across domains. In 1967, when Piaget's theory was more influential, it was thought that the development of reasoning and problem solving involved the acquisition of logical rules. It is now understood that inductive and deductive reasoning are influenced by similar factors and are subject to similar heuristics and biases in both children and adults.

7a. Deductive reasoning

Deductive reasoning problems have only one logically valid answer. An illustration is the logical syllogism. Given the premises:

> All cats bark
> Rex is a cat

the logically correct answer to the question 'Does Rex bark?' is yes. The plausibility or real-world accuracy of the premises does not matter for the validity of the logical deduction. When children are given syllogisms involving familiar premises, even if they are counterfactual (as in barking cats), they can make logically valid deductions (for example Dias and Harris 1988). Presenting the premises in play situations (for example pretending to be on a planet where cats bark) helps young children to reason logically, but 4 year olds can also succeed simply by being asked to think about the premises (Leevers and Harris 2000). When told, 'All ladybirds have stripes on their backs. Daisy is a ladybird. Is Daisy spotty?', one 4 year old commented, 'All ladybirds have stripes on their back. But they don't,' and then made the logically valid deduction. Even young children recognise that the premises, whatever they may be, *logically imply* the conclusions.

7b. Inductive reasoning

Although there is no logical justification of induction (Hume 1748/1988), inductive inferences are very useful in human reasoning. A typical inductive reasoning problem might take the form 'Humans have spleens. Dogs have spleens. Do rabbits have spleens?' (see Carey 1985). As all the animals named are mammals, one can 'go beyond the information given' and reason by analogy that rabbits probably do have spleens. However, if the problem takes the form 'Dogs have spleens. Bees have spleens. Do humans have spleens?', people are more reluctant to draw an inductive inference. This is because the most important constraint on inductive reasoning is similarity. Inductive generalisation depends on the similarity between the premise and conclusion categories, the sample size, and the typicality of the property being projected (Heit 2000). Successful reasoning by analogy also depends on similarity, with similarity of relations (for example, causal relations) being most important (Goswami 1991). As noted in Section 1d, very young children can make analogies involving causal relations. Encouraging metacognitive reflection improves analogical skills in young children. Brown *et al*. (1989) demonstrated that children's inductive reasoning could be enhanced if they experienced a *series* of analogies, and if they were taught to look for analogies during problem-solving ('learning-to-learn'). For example, children aged 3, 4 and 5 years learned to transfer different solutions (stacking objects, pulling objects, swinging over obstacles) between problem pairs administered sequentially (A1-A2/B1-B2/C1-C2). By novel problem C2, 85 per cent of 3-year-olds were successfully solving the problem by using an analogy.

Implications for education

Young children do not acquire the 'rules of logic' as they get older, rather they reason both inductively and deductively in the same ways as adults. Developmental differences arise from having a smaller knowledge base and from having less expertise: young children are 'universal novices' (Brown and DeLoache 1978). Learning from examples (by analogy) is a powerful form of human learning. Research by Brown suggests that instructional analogies work best when teachers present a series of examples of a particular concept within an explicit framework that emphasises relational similarity, making the goals (causal structure) of the teaching transparent. A key factor in transfer of learning is recognition of underlying similarity at the level of structure, often called "far transfer".

8. Cognitive prerequisites for reading and number

The invention of orthographic systems (for example the alphabet) and the number system (for example Arabic numerals) transformed human cognition, enabling the organisation of cognitive behaviour (learning, memory) by using symbols. These symbol systems require direct teaching, but for both reading and number there are cognitive prerequisites that facilitate learning. These prerequisites will be covered extremely briefly. Reading development builds on the cognitive representations for spoken language ('phonological representations'). Number builds on the cognitive representations for objects and quantities.

8a. Reading acquisition

There are multiple factors underpinning reading acquisition: cognitive and metacognitive, motivational, communicative, sociocultural, and so on. The most important cognitive pre-requisite skills for reading are described by the term 'phonological awareness'. Phonological awareness refers to a child's ability to reflect upon the sound patterns of words in her mental lexicon at different 'grain sizes' (for example syllable, rhyme). Phonological awareness is usually measured by tasks requiring the detection (for example, 'Which is the odd word out? "Hat, mat, fan?"') or manipulation ('What would "star" be without the "ss" sound?') of the component sounds that comprise words. As discussed earlier (Section 4a), an important part of language acquisition is phonological development. Children learn the sounds and combinations of sounds that are permissible in their language, forming 'phonological representations' for real words. Individual differences in the quality of these representations, measured by phonological awareness tasks, predict reading acquisition across languages (Ziegler and Goswami 2005). Awareness of syllables and rhymes develops prior to literacy across languages, but awareness of the smallest units of sound symbolised by letters (called *phonemes*) varies with orthographic transparency. Children learning languages with a 1:1 mapping from letter to sound (for example Finnish, German) rapidly acquire awareness of phonemes. Children learning languages that lack a 1:1 mapping from letters to sounds (for example English, French) acquire phoneme awareness more slowly. Phoneme awareness depends on teaching, because the phoneme is not a natural speech unit. Although the relative distributional frequencies of different acoustic features yield phonetic categories like 'p' and 'b' (see Section 4a), 'p' does not represent the same physical sound in words like 'pit' and 'spoon'. Hence the development of phonemic awareness depends in part on the consistency with which letters symbolise phonemes.

Providing training in phonological awareness at all grain sizes including supra-word prosodic patterning and training children in how phonological units link to letters enhances reading development across languages (for example, English: Bradley and Bryant 1983; Danish: Lundberg, Frost and Petersen 1988; German: Schneider, Roth and Ennemoser 2000). Nevertheless, reading efficiency is acquired at different rates in different languages (Seymour *et al.* 2003). Fluency is acquired fastest in languages where the mapping from letter to sound is 1:1, where syllable structure is simple (consonant-vowel syllables), and where there are relatively few phonemes (for example Finnish has 21 phonemes, or 25 if foreign loan words are counted). Fluency is acquired more slowly in languages with inconsistent spelling systems, many phonemes (English has around 44), and where syllable structure is complex (English has relatively few consonant-vowel syllables). Similarly, developmental dyslexia manifests differently in different languages. Children with poor phonological skills and reduced sensitivity to rhythm are at risk for dyslexia in all languages. Exercises to improve awareness of language rhythm (eg based on music and poetry) can facilitate reading development (Bhide, Power & Goswami, 2013). However, whereas dyslexic children learning to read a non-transparent language like English continue to experience problems in reading accuracy, for transparent languages like Finnish dyslexia manifests as extremely slow reading *speed* and poor spelling.

8b. The acquisition of number

The acquisition of number is currently a 'hot topic' in cognitive neuroscience. One popular view is that physiological/cognitive structures in the parietal lobe, shared by many species, provide an innate "number sense" upon which cognitive knowledge about number can build (for example Feigenson *et al*. 2004). However, while there is convincing evidence that these parietal structures support an approximate, analogue magnitude representation in many species (for example Dehaene 1997), it does not follow that children have an innate understanding of symbolic number. This number sense is an analogue representation, meaning that numbers are not stored mentally as discrete entities reflecting exact quantities, but as approximations of different quantities. As quantities get larger, representations get correspondingly less precise. Indeed, experiments with infants and young children show that the ability to make discriminations between quantities is ratio-sensitive (for example Jordan and Brannon 2006). For example, children are worse at comparing 8 with 12 (ratio

2:3) than 8 with 16 (ratio 1:2). For very small numbers (1 – 4), infants and young children rely on automatic perceptual processes called 'subitizing'. Subitizing is the fast perceptual enumeration of very small sets (the number is seen 'at a glance', Barth *et al*. 2005). Accordingly, young children's number skills are only accurate with very small numbers. Indeed, general cognitive skills such as visuo-spatial working memory, attention and inhibition (see section 6) play important roles in the development of facility with number.

One critical factor for building a cognitive number system from these basic spatial and perceptual representations appears to be learning the count sequence. Counting is first learned as a linguistic routine, like a nursery rhyme or the days of the week. The language of the count sequence captures number meaning in terms of both a distinctive individual quantity ('cardinality') and a quantity with a fixed place among other numerical quantities that is dependent on increasing magnitude ('ordinality'). This means that a number label in the count sequence, such as 'four', represents the fact that 4 cats is the equivalent amount to 4 biscuits, and that 4 has a magnitude between 3 and 5. Learning to count enables children to organise their cognitive structures for number (subitizing and the analogue magnitude representation) into a coherent system. Accordingly, certain cross-cultural differences in the set of number names have some cognitive consequences, although these are brief and occur around age 2 (for example Hodent *et al.* 2005). By around 3 years, children are developing the expectation that even unmapped number words refer to exact numerosities (Sarnecka and Gelman 2004). Number knowledge such as the 'number facts' (for example the multiplication tables, 2 + 2 = 4 et cetera) are stored in the language areas of the brain, and not in the spatial area where the analogue magnitude representation is found (Dehaene *et al.* 1998). Other cognitive prerequisites for understanding mathematical operations, such as 1:1 correspondence for division, are reviewed by Nunes and Bryant (1996).

Implications for education

The cognitive prerequisites for reading and number depend on language development, perceptual development, spatial development and working memory. A child with poor phonological awareness at school entry will have more difficulty in learning to read, and a child with poor spatial skills will have more difficulty in acquiring symbolic number. The development of an awareness of syllables and rhyme is important for learning about phonemes. The ability to count accurately is important for learning about numbers. Developmental dyslexia and developmental dyscalculia are specific learning difficulties. While developmental dyslexia is widely thought to reflect specific problems with phonology (Snowling, 2000), the sensory basis of developmental dyscalculia is currently debated (for example Molko *et al*. 2003; Szucs *et al.* 2013).

9. Theories of cognitive development and intelligence

As noted earlier, Piaget's theory that children reason in qualitatively different ways at different developmental stages is no longer accepted (see Section 2). Whereas the Plowden Report assumed that children only became capable of logical thought based on symbolic and abstract material in adolescence (Plowden 1967: 50), today child psychology assumes that all the basic forms of learning and reasoning are available from baby- and toddler-hood. What develops is the child's knowledge base, along with skills like working memory, metacognition and self-regulation (executive function). However, Plowden was correct to note that the development of language is central to the educational process (Plowden 1967: 54-55). Language is a symbolic and abstract system, and via language, pretend play and the imagination, even very young children think logically with abstract material (for example see Section 7a). This is most clearly demonstrated in Vygotsky's theory of cognitive development (Vygotsky 1978, 1986).

9a. Vygotsky

Vygotsky argued that language is the primary symbolic system and that, once acquired, language mediates cognitive development. As speech becomes internalised ('inner speech'), it becomes fundamental in organising the child's cognitive activities. 'Sign systems' or 'psychological tools' such as language, drawing and writing are culturally transmitted, and so the inter-relatedness of social and cognitive processes in children's learning is fundamental. Eventually, sign systems will mediate psychological functioning *within* the child, primarily via inner speech. The importance of learning from others is also highlighted by Vygotsky's notion of the 'zone of proximal development' (ZPD). The ZPD differs between children, and essentially measures how much further a child can go when learning with the support of a teacher. Vygotsky's recognition that learning can change the child's developmental level suggests that teachers need to discover an individual child's ZPD and teach to that level in order for instruction to bring optimal benefits. Vygotsky also argued that play, in particular the creation of imaginary situations, plays a central role in cognitive development. Joint pretend play requires recognition of the 'rules of the game' and aids the development of self-regulation, as children have to play by the rules. Play in itself creates a zone of proximal development, and while children are highly motivated to play, teachers have an important role in deliberately creating ZPDs via play in scenarios that support learning (Karpov 2005).

Russian neo-Vygotskyians (for example Karpov 2005) have also stressed the role of joint activity with adults for the effective use of the zone of proximal development in teaching. They argue that verbal mediation is not enough to optimise learning. Shared activity is required to mediate the child's acquisition, mastery and internalisation of new content. Mediation should begin with the adult explaining and modelling the procedure or material to be learned. The adult should then involve the child in joint performance of this procedure or material, thereby creating the ZPD for the development of a new mental process. The child's mastery and internalisation of the material should then be guided until the adult can begin to withdraw. Neo-Vygotskyians have also focused on an approach called 'theoretical learning'. This offers an alternative to the constructivist learning pedagogies based on Piaget's theory. Rather than being required to rediscover scientific knowledge for themselves, children taught by theoretical learning are taught precise definitions of scientific concepts. They then master and internalise the procedures related to these concepts by using the conceptual knowledge to solve subject-domain problems (Karpov 2005). Although claimed by Russian psychologists to be highly effective, Western psychology has not yet studied Vygotsky's ideas about theoretical learning or his ideas about the role of play in education in any detail.

9b. Neuroconstructivism

Neuroconstructivism is a theoretical framework for cognitive development emerging from cognitive neuroscience. It is based on a consideration of the biological constraints on the patterns of brain activity that comprise mental representations, for example the biological action of genes (Mareschal *et al*. 2007; Westermann *et al*. 2007). Genetic activity is modified by neural, behavioural and external environmental events, and all of these interactions must be understood in order to describe cognitive development. Similarly, the ways in which the human senses function will constrain the development of mental representations, as the senses 'filter' information from the environment. For example the human ear can only hear a certain range of sound frequencies, there are sounds present in the environment that we do not hear.

Neuroconstructivism is important for understanding developmental cognitive disorders, as these are explained by altered constraints on brain development (such as atypical sensory functioning) that in turn alter a child's developmental trajectory (for example Karmiloff-Smith 2007). As an example, altered sensory functioning in the auditory system (reduced sensitivity to speech rhythm) could explain why children with developmental dyslexia do not develop well-specified phonological representations (for example Goswami 2003, 2015). However, our understanding of the biological constraints that affect the development of the neural structures that underlie cognitive processing is still very incomplete. Neuroconstructivism is not deterministic, as it foregrounds the quality of the learning environment. The progressive specialisation of neural structures is driven by the environment experienced (and actively chosen) by the child. Neuroconstructivism offers a biological perspective on cognitive development, while connectionism (Section 1e) offers a biological perspective on learning.

9c. Theories of intelligence

Intelligence received a lot of attention in the Plowden Report (CACE 1967: 56-64). The strong heritability of intelligence is now accepted, but the emphasis in research is on the key role of the environment for explaining variability (for example Ashbury & Plomin 2013). An influential idea in education has been that of 'multiple' or distinct intelligences (Gardner 1993, 1999; for example 'spatial intelligence', 'logical-mathematical intelligence', 'linguistic intelligence'). This theory grew from a modular view of the brain, which is less applicable developmentally (for example Johnson & de Haan, 2011). The developing brain is a highly interactive system and knowledge will be distributed across neural networks in a number of regions (spatial and linguistic knowledge underpin mathematical performance, for example). The idea of multiple intelligences is a useful metaphor for emphasising that intelligence reflects a range of skills (note however that Gardner himself did not consider multiple intelligences to be an educational goal).

Multivariate genetic research shows substantial genetic overlap between broad areas of cognition such as language, memory, mathematics and general cognitive ability (Kovas and Plomin 2006). Hence within the average child, genes are 'generalist' in their effects, and there are typically strong associations between ability in one area of cognition and ability in another. The fact that genes influence development makes it even more important to provide optimal early learning environments for all children. If learning environments are optimal, individual differences will emerge because of genetic differences. By contrast, if some children experience poor-quality learning environments while others do not, individual differences between children will be much larger, because developmental impairments caused by a poor environment will be *added* to any impairments caused by genes.

Dweck (1999, 2006) has emphasised the importance of children's self-theories of intelligence for their response to schooling. Her research shows that some children have an entity or fixed theory of intelligence, which leads them to consider effort as negative (if learning requires effort, they cannot be intelligent) and to adopt performance goals (for example scoring well on tests). Other children have an incremental or growth theory of intelligence, seeing it as a malleable quality that can be changed by effort. These children adopt learning goals and feel that they need to work harder if they do not understand something. Dweck's research suggests that children's beliefs about intelligence can be altered by feedback from teachers, who should try and praise effort rather than performance. Dweck shows that receiving praise for effort rather than for performance increases the motivation to learn.

Implications for education

While the new theoretical frameworks of neuroconstructivism and connectionism are important for understanding how the brain creates cognitive representations from perceptual input, the older theoretical frameworks of Piaget and Vygotsky are important for understanding how the activities of the child and the parent/sibling/peer/teacher enrich and develop these cognitive representations into a sophisticated cognitive system. Note that all theoretical frameworks attest to the importance of the quality of the learning environment. Given current levels of knowledge, we can conclude that an educational focus on language and imaginative play, on knowledge construction, on direct and dialogic teaching and on being part of a learning community are all important for the education of the primary school child. The notion of multiple intelligences is important in encouraging flexibility in teaching, for example approaching educational topics in different ways and using analogies from a variety of domains. Learning is strengthened by expressing key concepts in a variety of forms (for example Gardner 2003). The kind of feedback offered in the classroom is very important for the child's self-esteem and for their view of themselves as a learner. The human brain is a social brain, and learning by children is primarily a social activity. Furthermore, teachers' expectations can be transmitted to the social brain implicitly, without conscious intent.

Some conclusions

This report documents some central aspects of child development, thinking and learning in the primary years. Some key conclusions are:

- Learning in young children is socially mediated. Families, peers and teachers are all important. Even basic perceptual learning mechanisms such as the statistical learning of linguistic sounds requires direct social interaction to be effective. This limits the benefits of educational approaches such as e-learning in the early years.

- Learning by the brain depends on the development of multi-sensory networks of neurons distributed across the entire brain. For example, a concept in science may depend on neurons being simultaneously active in visual, spatial, memory, deductive and kinaesthetic regions, in both brain hemispheres. Ideas such as left-brain/right-brain learning, or unisensory 'learning styles' (visual, auditory *or* kinaesthetic) are *not* supported by the brain science of learning.

- Children construct explanatory systems to understand their experiences in the biological, physical and psychological realms. These are implicit causal frameworks, for example that explain why other people behave as they are observed to do, or why objects or events follow observed patterns. Knowledge gained through active experience, language, pretend play and teaching are all important for the development of children's causal explanatory systems. Children's causal biases (eg. the essentialist bias) should be recognised and built upon in primary education.

- Children think and reason largely in the same ways as adults. However, they lack experience, and they are still developing important metacognitive and executive function skills. Learning in classrooms can be enhanced if children are given diverse experiences and are helped to develop self-reflective and self-regulatory skills via teacher modelling, conversation and guidance around social situations like play, sharing and conflict resolutions.

- Language is crucial for development. The ways in which teachers talk to children can influence learning, memory, understanding and the motivation to learn. There are also enormous individual differences in language skills between children in the early years. Interactions around books are one of the best ways of developing more complex language skills.

- Incremental experience is crucial for learning and knowledge construction. The brain learns the statistical structure of 'the input'. It can be important for teachers to assess how much 'input' a child's brain is actually getting when individual differences appear in learning. Differential exposure (for example to spoken or written language) will lead to differential learning. As an example, one of the most important determinants of reading fluency is how much text the child actually reads, including outside the classroom.

- Thinking, reasoning and understanding can be enhanced by imaginative or pretend play contexts. However, scaffolding by the teacher is required if these are to be effective.

- Individual differences in the ability to benefit from instruction (the zone of proximal development) and individual differences between children are large in the primary years, hence any class of children must be treated as individuals.

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