Trends in Applied Cognitive Development

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Trends in Applied Cognitive Development

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Abstract
This paper provides an overview of key research conducted locally and internationally in the field of applied cognitive development, particularly working memory and executive functioning from early childhood to mid-adolescence. The focus is on understanding the reasons for low achievement in children, with a particular emphasis on the interaction of domain-specific knowledge, attentional, social-emotional, and motivational predictors of academic achievement. We also focus on research examining the efficacy of interventions to enhance cognitive, social-emotional, and academic skills. We highlight the directions in which we believe future work should proceed given current developments in the field, our own interests and core capacity, and the need to address important educational questions in Singapore. These include the need to develop more sensitive tests of specific cognitive abilities, continued efforts to develop interventions to support the development of both domain-general skills and domain-specific numeracy and mathematics skills, an understanding of individual differences in response to pedagogy and training, and the examination of social-emotional factors (e.g., anxiety) on cognition and learning. Continued collaborative efforts will allow us to address these questions with behavioural, physiological, and neurological data and will provide a deeper understanding of the child’s outcomes in response to the pedagogical environment.

Background and Introduction
This paper presents a review of international and local research situated at the interface between the cognitive, developmental, and educational sciences. Special focus is paid to the development of higher cognitive abilities of children from early childhood to adolescence, in particular working memory (WM) and executive functioning (EF). Key trends and current perspectives are identified

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and future directions are discussed. Lastly, some recommendations are described.

**External Scan**
Several lines of research have dominated the area in recent years: (a) investigations of relations between executive functioning, self-regulation and academic performance; and (b) work on cognitive training, neuroplasticity, and the effects of self-regulatory and cognitive enhancement activities on various developmental outcomes. Parallel to these efforts are developments in techniques for measurement of these concepts and statistical analysis of the data.

**Executive functions, attentional and emotional self-regulation**
EF is commonly defined as processes that control, direct or coordinate other cognitive processes, but both its conceptualization and measurement vary across studies. Early studies focused on the central executive component of Baddeley and Hitch’s (1974) WM model, and typically assessed its capacity using span tasks requiring simultaneous processing and storage of information. Baddeley (1996) argued for a more expansive view of the central executive, and Miyake, Friedman, Emerson, Witzki, Howarter, and Wager (2000) published a highly influential paper on the unity and diversity of EF. They discussed EF in terms of inhibition (ability to suppress or resist irrelevant information, processes or responses), shifting (switching flexibly between tasks or mental sets) and updating (monitoring and the addition or deletion of contents from WM). Although the concepts of WM and updating are not identical (processing and recall versus the selective replacement of information from a mental workspace), performance on span and updating tasks appear to be closely related (St Clair-Thompson & Gathercole, 2006; Wilhelm, Hildebrandt, & Oberauer, 2013). EF is the foundation for higher order skills such as reasoning, problem-solving and planning (Diamond, 2012; Miyake et al., 2000a). More recent work has focused on understanding the development of EF, especially in terms of its organization and rate of growth, as well as its development in relation to other social and environmental factors. A few studies have found that the components of EF are not well-differentiated in younger children unlike in adults.
(Hughes, Ensor, Wilson, & Graham, 2010; Lee, Bull, & Ho, 2013; Wiebe et al., 2011), but rather that differentiation takes place over a protracted period of development.

EF is closely related to attention and emotional regulation. Sustaining attentional focus under affectively neutral conditions (referred to as “cool EF”) requires: (a) the maintenance of task rules in WM; (b) inhibiting attention to distracting irrelevant stimuli; and (c) switching attention back to the task at hand when distracted. Emotional regulation (referred to as “hot EF”) requires attentional control in affective and motivational contexts, e.g., inhibiting attention to and shifting attention away from an attractive toy that is not supposed to be played with, or shifting attention away from distressing stimuli—a skill observable from early infancy (Harman, Rothbart, & Posner, 1997; Zhou, Chen, & Main, 2011). Attention and inhibition in self-regulation is also commonly studied under effortful control (EC) in socio-temperamental research. Some researchers have argued that EF and EC share enough communality to be interchangeable, and have advocated for an integrative account encompassing both perspectives (Zhou et al., 2011). Distinguishing hot from cool EF may be a step in this direction, with hot EF having a closer correspondence to EC than cool EF. Cool EF features more prominently in WM research, which is not typically examined as part of EC (Harman et al., 1997; Zhou et al., 2011).

The interaction of EF and attention in academic achievement
Self-regulation in childhood predicts a wide range of developmental outcomes, from school readiness and academic ability in childhood and adolescence to health and social-emotional problems in adulthood (Zelazo & Lyons, 2012). Long-term EF deficits have been associated with premature birth and prenatal exposure to alcohol (Hughes, 2011). Social environmental factors such as high maternal scaffolding and low family chaos were found to predict improvements in EF from the ages 2 to 4 (Hughes & Ensor, 2009). In a study spanning ages 4 to 6, verbal ability and family income predicted initial variation in EF at age 4, but only verbal ability was related to the rate of growth in EF. That is, across the transition to school, verbally less able children, but not children from low income families, began to
catch up with their peers (Hughes et al., 2010). Such findings highlight the importance of examining EF developmental trajectories for both theory and (educational) policy development (Hughes, 2011).

In relation to learning outcomes, difficulties in lesson comprehension due to early attention problems and poor EF can lead to widening achievement gaps across development (Rabiner & Malone, 2004; Roebers, Cimeli, Röthlisberger, & Neuenschwander, 2012). Individual differences in EF are related to literacy, writing and science achievement (e.g., Bull, Espy, & Wiebe, 2008; Monette, Bigras, & Guay, 2011; Neuenschwander, Röthlisberger, Cimeli, & Roebers, 2012), although some studies report that the direct effects of EF seem especially strong for mathematics (Bull, Espy, Wiebe, Sheffield, & Nelson, 2011; Lee, Ng, & Ng, 2009; Van der Ven, Krosesbergen, Boom, & Leseman, 2012). Longitudinal studies suggest that EF contributes to later academic performance. For example, WM at age 29–41 months predicts classroom engagement, numeracy and vocabulary skills in kindergarten, above and beyond gender, verbal and non-verbal intellectual skills, and socio-economic status (Fitzpatrick & Pagani, 2012). Not only has EF been found to correlate with mathematical and reading abilities from ages 5–17 years (Best, Miller, & Naglieri, 2011), better short-term memory and EF provide children with a head start in math and reading, which was maintained throughout the first 3 years of primary school (Bull et al., 2008). A recent longitudinal study also found that EF predicted academic achievement in 5- to 8-year-olds, and that academic achievement also depended on their initial EF levels (Röthlisberger, Neuenschwander, Cimeli, & Roebers, 2013). Pre-schoolers with low EF tend to perform more poorly in math and reading 2 years later, compared to those who started pre-school with medium and high EF.

Keeping in mind their overlap with EF, similar outcomes have been found with early attention abilities. Early attention problems have been found to predict later academic achievement (especially math and comprehension) and behavioural competence, even after controlling for factors such as intelligence, SES, maternal warmth and infant temperament (Polderman, Boomsma, Bartels, Verhulst, & Huizink, 2010; Polderman et al., 2011; Razza, 2012). For example,
attentional failures in the form of mind wandering during reading can impair the encoding of information and subsequent depth and quality of processing and comprehension (Schooler, Reichle, & Halpern, 2004; Smallwood, Fishman, & Schooler, 2007). Affected students may subsequently fail to acquire a wide range of academic skills and knowledge increasingly required for subsequent learning (Flory et al., 2006; Horn & Packard, 1985; Rudasill, Gallagher, & White, 2010). Attention has also been found to partially mediate the link between academic performance and ethnicity (Rabiner, Murray, Schmid, & Malone, 2004), family environment (Network, 2003), and intelligence (Steinmayr, Ziegler, & Träuble, 2010).

**Interaction between hot and cool EFs—cognition and emotion**

Substantial research has focussed on the role of EF, attention, and emotional factors such as anxiety and motivation in learning outcomes (Bull & Scerif, 2001; Ergene, 2003; Hembree, 1988; Long, Seely, & Oppy, 1999; Passolunghi & Siegel, 2001). Earlier work tends to examine the role of EF, attention and emotional factors such as anxiety and motivation in learning outcomes separately. However, more recent work highlights the interactive relationships between top-down cognitive and bottom-up emotional influences on learning and performance. For example, it is known that whilst anxiety has a negative impact on math performance, not all high math-anxious students perform poorly in math. Reasons thought to underlie such differences were typically differences in motivation, study- or math-specific skills. Recent models of test anxiety postulate poor inhibitory control of attention to distractors (e.g., worry) as underlying the adverse effects of anxiety on WM and performance (Eysenck, Derakshan, Santos, & Calvo, 2007). Functional neuroimaging studies show that math-anxious students’ math performance depended on their ability to regulate cognitive resource allocation in the face of negative emotional arousal, which then influenced the utilization of motivational resources during the task itself. It was suggested that educational interventions that focus on enhancing cognitive control in the face of negative arousal may be helpful for the high-math anxious (Lyons & Beilock, 2011). In fact, school readiness has been said to be characterized by the integration of cognitive-emotional control (Blair & Diamond, 2008). Arousal due to stress as indicated physiologically by
higher salivary cortisol baseline levels are associated with poor EF in pre-school children (Blair, Granger, & Peters Razza, 2005).

**Cognitive training**

Fuelled by findings on the prominence of attention and EF in learning outcomes as well as on neuroplasticity, the recent years have seen a surge in the development and evaluation of cognitive training programmes. Interventions or activities that have been found efficacious in improving EF range from training on computerized and non-computerized game-like tasks; physical activities such as aerobic exercise, yoga and martial arts; music training; to mindfulness-based school curricula (Barkl, Porter, & Ginns, 2012; Best, 2010; Diamond, 2012; Diamond, Barnett, Thomas, & Munro, 2007; Diamond & Lee, 2011; Goldin et al., 2014; Holmes & Gathercole, 2014; Jaeggi et al., 2010; Kroesbergen, van’t Noordende, & Kolkman, 2014; Moreno et al., 2011; Rueda, Checa, & Cómbita, 2011; Shipstead, Redick, & Engle, 2010; Stevens & Bavelier, 2011).

Improvements have been observed in children from age 4 to 5 years through adolescence and adulthood, though results vary across groups and types of training. Some EF and WM interventions demonstrate enduring or long-term improvements (e.g., up to 6 months after training), as well as transfer to untrained tasks such as fluid intelligence, inductive reasoning, affect regulation, other EF, numeracy skills and school academic performance (Barkl et al., 2012; Goldin et al., 2014; Holmes & Gathercole, 2014; Holmes, Gathercole, & Dunning, 2009; Jaeggi et al., 2010; Karbach & Unger, 2014; Kray & Ferdinand, 2013; Kroesbergen et al., 2014; Moreno et al., 2011; Rueda et al., 2011; Thorell, Lindqvist, Bergman Nutley, Bohlin, & Klingberg, 2008). More integrative forms of training that strengthen top-down cognitive control processes while lessening bottom-up influences such as stress and anxiety may also be effective (Zelazo & Lyons, 2012). For example, compared to a physical-training control group, 10- and 13-year-old girls randomly assigned to a month of daily yoga (comprising physical training, relaxation and sensory awareness) showed greater improvement on EF tasks (Manjunath & Telles, 2001). Changes at the neural level have been observed even after short periods of training (Moreno et al., 2011; Rueda et
al., 2011). For example, electroencephalogram (EEG) recordings showed more efficient activation of attentional resources in 5-year-olds following 10 sessions of training on computerized attention tasks (Rueda et al., 2011). However, although trait-like changes have been found with some forms of long-term attention training in adults (Lutz, Slagter, Dunne, & Davidson, 2008), it is not known to what extent brief training results in enduring neurofunctional enhancements in children.

The general conclusion is that cognitive training works. It tends to provide greater benefit to children with poorer beginning status by giving them an opportunity to “catch up” with their peers (Diamond, 2012; Diamond & Lee, 2011); and may have greater potential for benefit in younger children (Kray & Ferdinand, 2013; Melby-Lervåg & Hulme, 2013). However, a meta-analysis and some recent adult studies suggest that brief interventions may not be as effective as initially thought (Chooi & Thompson, 2012; Melby-Lervåg & Hulme, 2013; Redick et al., 2013; Thompson et al., 2013). The continuing challenge is in clarifying the conditions for training success, such as age at intervention, dosage and length of the intervention, matching training task to individual profiles, as well as appropriate forms of assessment or outcome measures (Diamond, 2012; Jaeggi et al., 2010).

**Interaction between school/classroom practices and cognitive development**

One question is whether academic development also contributes to EF development (Best et al., 2011). In some African cultures where there is large variation in schooling, childhood exposure to schooling has been found to be associated with higher EF and cognitive abilities in adulthood (Baker, Salinas, & Eslinger, 2012; Peters, Baker, Dieckmann, Leon, & Collins, 2010). A number of growth modelling and intervention studies have demonstrated “catch up” effects (Diamond, 2012; Diamond & Lee, 2011; Hughes et al., 2010). Others found improved EF following activities commonly available in school such as music and exercise (Best, 2010; Moreno et al., 2011). These studies suggest that school activities can contribute to the development of EF, but effects vary with the type of activity. For example, “cognitively engaging” physical exercises such as those involving complex motor coordination or strategizing and group interaction, are superior
to less challenging, repetitive, physical exercises (Best, 2010); a computerized music training programme—thought to require high levels of control and attention—was more effective than a computerized visual art training programme (Moreno et al., 2011). It has been suggested that effects on EF may depend on the extent the activities engage EF.

The success of curricular and co-curricular programmes in enhancing EF and self-regulation (Diamond et al., 2007; Flook et al., 2010; Lillard & Else-Quest, 2006; Raver et al., 2011; Riggs, Greenberg, Kusché, & Pentz, 2006) prompted researchers to advocate educational programmes with activities that encourage the “emerging balance between processes of emotional arousal and cognitive regulation” and promote social-emotional competencies (Blair & Diamond, 2008; Liew, 2011; Zelazo & Lyons, 2012). These include pre-school programmes such as Tools of the Mind (Bodrova & Leong, 2007), Montessori (Montessori, 2002) and the Chicago School Readiness Project (CSRP) (Raver et al., 2008), elementary school programmes such as Promoting Alternative Thinking Strategies (PATHS) (Kusché & Greenberg, 1994), and a variety of mindfulness-based programmes for children from K1–12 (~5–18 years) (Meiklejohn et al., 2012). While most of these programmes had been created for school children, mindfulness-based programmes were developed from practices that have had a longer and broader history in adult attention training with demonstrated efficacy extending to clinical and organizational settings (Chiesa, Calati, & Serretti, 2010; Lutz et al., 2008). Findings of enhanced neural connectivity between top-down cognitive control and bottom-up sensory networks following 8 weeks of mindfulness attention training in adults adds neurofunctional evidence of an enhanced regulatory system (Kilpatrick et al., 2011).

**Methodological developments**

Accurately indexing covert abilities or processes is a continual challenge in the behavioural sciences, especially with fundamental process functions such as EF or more complex cognition such as thinking or understanding.
**Behavioural measurement**

EF is commonly assessed with a few broad categories of tasks, ranging from self- or other-rated behavioural questionnaires (e.g., Behavioural Rating Inventory of Executive Function, BRIEF, Gioia, Isquith, Guy, & Kenworthy, 2000), to simple choice reaction time and problem-solving tasks. Simple EF tasks (e.g., the Stroop task, Stroop, 1935) measure specific functions (e.g., inhibition) while overall performance on complex EF tasks (e.g., Wisconsin Card Sorting Task, WCST, Heaton, Chelune, Talley, Kay, & Curtiss, 1993) are used to measure general EF. Performance sub-indices on complex EF tasks are also used to index specific componential EF.

However, the psychometric properties of many EF tasks are not well-established and often raise questions regarding task impurity and reliability (Miyake et al., 2000b; Willoughby, Wirth, & Blair, 2011): that is, do the tasks accurately and consistently assess the processes that they are meant to index? Some tasks that purportedly measure the same EF tend to be moderately or poorly correlated. There is also little work on the relation between subjective (e.g., parent/teacher-rated BRIEF) versus “objective” measures of EF (e.g., Stroop and WCST). Finding an appropriate task that measures the same function across the entire lifespan is also challenging (Röthlisberger et al., 2013; Willoughby et al., 2011), especially in view of recent findings regarding the late differentiation of EF components in childhood. Within tasks, the choice between accuracy or reaction time (RT) scores is also a conundrum as the pattern of results may differ, confounded by individual and developmental differences in speed-accuracy trade-offs (Leon-Carrion, Garcia-Orza, & Pérez-Santamaría, 2004). Recent trends in EF/cognitive measurement and analysis of behavioural data include examining entire RT distributions using techniques that allow for more precise measurements and detailed tests of hypotheses (Bub, Masson, & Lalonde, 2006; Fagot, Dirk, Ghisletta, & De Ribaupierre, 2009; Ratcliff, Love, Thompson, & Opfer, 2012). “Given the relation of executive functions to a number of aspects of child development… research on the measurement of executive function in young children is a scientific priority.” (Willoughby et al., 2011, p. 14).
Neurobiological measurement
Increasing attempts at assimilating findings from neuroscience to inform educational practice has prompted the proposition that the school can be viewed as a “neurocognitive developmental institution” (Baker et al., 2012) that can potentially aid in “levelling the playing field” and reduce widening achievement gaps. The recent years have seen efforts in using neurophysiological methods in educational contexts, for example, in the diagnosis of academic difficulties and the evaluation of interventions when behavioural measures are not sufficiently sensitive or appropriate (Blair et al., 2005; Blakemore & Bunge, 2012; Rueda et al., 2011). Other examples include using neural reactivity measured by event-related potentials to predict academic aptitude and using cortisol reactivity as a more objective index of stress in a study on the efficacy of intervention curricula (Blair et al., 2005).

Neurophysiological measurements may be especially useful given the current lack of clarity regarding the boundary conditions of cognitive training. Deterrents to wider usage are high cost and compromises in ecological validity. The latter is often necessitated by the use of functional magnetic resonance imaging (fMRI) or EEG. Functional magnetic resonance imaging provides information on which parts of the brain are being activated during a task. However, it requires participants to lie still in a scanner and each scan is very costly. In recent years, some of these concerns have been addressed partially by new technological advancement. Both functional near-infrared spectroscopy (fNIRS) machines and wireless EEG headsets are relatively more portable and affordable. However, both suffer from limitations in the kind of brain activities that can be measured. With further translational studies, these tools could potentially be useful for studying behaviours in ecologically valid settings (e.g., during a classroom lesson or learning activity).

Analysis
The increasing use of more sophisticated statistical techniques such as confirmatory factor analyses, item response theory, latent growth models and other structural equation models, have also allowed for better control over reliability issues related to task impurity, subtraction scores (Lord, 1956) or measurement error (Miyake et al., 2000b).
Such techniques can enable a more comprehensive examination of the interplay among various factors in longitudinal data, which is important for identifying specific factors that warrant early intervention to minimize school failure. Future studies using such techniques along with data from (newer) behavioural and neurophysiological measures of cognitive processing will present a clearer picture of cognitive development in children.

**Internal Scan**

This section gives an overview of recent and current work on applied cognitive development at NIE. The overarching objective of the work conducted within the Applied Cognitive Development Lab (ACDL) is to understand the domain-specific and cognitive developmental predictors of academic achievement, and to develop effective interventions for low-achieving children. In line with this, current research foci include:

- The role of EF and WM in children’s math achievement.
- The role of domain-specific predictors in children’s early mathematical skills, and the sources of individual differences in children’s early number skills prior to formal schooling.
- The early identification of children at risk of mathematical learning difficulties.
- The interaction of cognitive and affective variables in learning and performance.
- The development of sensitive tests to assess individual differences in EF.
- The relationship between attention and test anxiety, including intervention techniques to support attentional skills and reduce anxiety.
- Development of cognitive, physical and attentional interventions to support the learning of low-achieving children.
- The integration of a range of measurement methods including behavioural, physiological and neurological techniques.

We highlight some of these key areas in this paper. In combination with evidence provided in the external scan, we end with some ideas for future research directions and educational recommendations.
Role of domain-general cognitive abilities and domain-specific numerical skills in supporting mathematical ability

As a domain-general cognitive ability, EF is important for the development of academic skills even prior to formal schooling, and poor EF may have a cumulative effect on school achievement. Children with poorer EF may have difficulties acquiring skills both in the course of maturation, and through instruction in the classroom. They tend to make more errors in learning activities due to difficulties with remembering and carrying out instructions, inhibiting irrelevant information, staying focused on a task, and monitoring progress and switching to more appropriate task strategies (Bull & Lee, 2014). In particular reference to the development of mathematical skills, an important task is to understand the unique and shared roles played by these domain-general abilities and simpler numerical skills in supporting continued learning of increasingly complex mathematical knowledge and procedures.

Algebraic skills

Our laboratory’s research programme began with a series of cross-sectional studies on primary school children examining the cognitive underpinnings of mathematical and algebraic proficiency, and factors that contribute to individual differences in mathematical performance. In an early study, we found WM explained about 21% of variance in Primary 5 children’s performance on algebraic word-problem tasks (Lee, Ng, Ng, & Lim, 2004). A follow-up study expanded the search for explanatory variables by including a battery of EF tasks measuring updating, inhibition and switching (Lee et al., 2009). The findings again pointed to the importance of updating. Using a dual task experimental manipulation, we found evidence for a causal link between availability of WM resources and performance on algebraic tasks (Lee & Ng, 2009).

A related line of work focused on the cognitive underpinnings of algebraic learning. In Singapore, math is taught as part of a spiral curriculum. Topics are taught and are subsequently built upon in later years. For algebra, children are given exposure to algebraic questions from as early as Primary 5, with a focus on algebraic thinking rather than algebra per se. Children are taught to conceptualize and solve problems using a mix of graphical and arithmetic algorithm that is
commonly referred to as the model method. It is generally not till secondary school when they are exposed fully to symbolic algebra, equations and their manipulations. One concern expressed by some teachers and parents is whether the same kind of thinking or skills is required by the model method and symbolic algebra. Does learning the model method help prepare children for symbolic algebra?

We found that amongst learners of symbolic algebra, higher algebra problem-solving proficiency was related to ability to inhibit intrusions from the model method (Khng & Lee, 2009). However, two functional neuroimaging studies, conducted with adults proficient in both symbolic algebra and the model method, found similar brain areas were activated by the two approaches (Lee et al., 2007; Lee et al., 2010). Furthermore, the symbolic method was found to activate areas associated with the use of attentional resources, suggesting that it is better suited for older children with greater access to such resources. One inference we drew from these findings is that to facilitate students’ transition from algebraic problems encountered in primary versus secondary school, linkages between the various problem-solving methods need to be made explicit. This will better allow students to leverage on their prior knowledge regarding the model method.

Pre-algebraic mathematical skills
Another recent study has focused on the effects of irrelevant information on arithmetic word-problem solving and the extent to which inhibitory abilities affect children’s abilities to solve such problems. Such word-problems are found in international evaluations like the Programme for International Student Assessment (PISA) and the Trends in International Mathematics and Science Study (TIMSS), and are thought to be more similar to real-world mathematical problems. Preliminary analyses suggest that irrelevant numerical information (e.g., “80 marbles”) but not literal irrelevant information (e.g., “some marbles”) resulted in poorer performance accuracy. Children’s abilities to classify whether information is relevant were found most predictive of accuracy.

Early pre-numeracy and mathematical skills
There has been a recent focus in our Lab to examine earlier developing numerical skills (referred to by some as “number
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sense”), and the utility of such skills in predicting later mathematical difficulties. One possible locus for a domain-specific deficit is the Approximate Number System (ANS). The ANS has been shown to support a primitive sense of number in infants, children and adults (for reviews, see Dehaene, 1997; Feigenson, Dehaene, & Spelke, 2004; Libertus & Brannon, 2009). The ANS is a mental system of approximate number representations that is activated and used during both non-symbolic approximations (e.g., judging which array of items is more numerous) and symbolic number tasks (e.g., understanding the quantitative relationships between numbers). Such skills have been found to predict children’s formal math ability over and above domain-general abilities such as WM (e.g., Halberda, Mazzocco, & Feigenson, 2008; Libertus, Feigenson, & Halberda, 2013; Lonnemann, Linkersdörfer, Hasselhorn, & Lindberg, 2013; Mussolin, Nys, Leybaert, & Content, 2012); for a meta-analysis see Chen and Li (2014).

One of our studies focused on the acuity with which children are able to represent and think about number in an approximate form, and how well this predicted concurrent and later math achievement as well as the need for learning support of math. Findings showed that kindergarten children who have less accurate representations of number showed consistently poorer performance (both concurrently and longitudinally) on a range of standardized math tests assessing basic arithmetic, arithmetical fluency and mathematical reasoning. Individual differences in approximation skill and math were predicted by opportunities to engage in numerical tasks: Children who were more likely to spontaneously focus on number in everyday tasks, and children who were attending math enrichment classes, achieved significantly higher scores on math and approximation outcome measures. Insights into these mechanisms that facilitate children’s early quantitative learning are critical to the development of interventions that put at-risk children on the path to numeracy. These results provide a number of targets for intervention, particularly for children from lower SES homes who may benefit from inexpensive numerical experiences (e.g., number games) in the home or pre-school. Although research has demonstrated the short-term benefits of such games, studies of the long-term benefits are still required,
particularly in terms of their efficacy in reducing the number of children who may require learning support for math.

Another study examined the unique and shared roles of domain-general (i.e., WM) and domain-specific abilities (i.e., symbolic and non-symbolic magnitude discrimination) in Primary 1–3 children’s mathematical performance. Findings showed that contrary to our findings in kindergarten children, most of the magnitude discrimination measures did not account for variance in performance on standardized mathematical tests when WM and intelligence were taken into consideration. Although it is difficult to compare across studies as there are differences in the task used for measuring magnitude discrimination abilities, these findings suggest that even the Primary 1 children had sufficiently advanced mathematical knowledge—so much so that number sense acuity did not reflect individual differences in mathematical performance.

We have also just finished a 5-year longitudinal study in which we tracked children’s developing abilities in EF (Lee, Bull, et al., 2013) and examined how they corresponded with evolving skills in math. The data showed that children’s updating capacity was strongly correlated with concurrent performance in a standardized math test. This relation peaked in Primary 1 and 2 (7- and 8-year-olds). Although both domain-general and domain-specific abilities predicted performance through much of the primary schooling years, data from the 7- and 8-year-olds suggested that most children at this stage have acquired the necessary fundamental numerical knowledge and performance in the math task relied primarily on updating capacities. Together with evidence for a causal relation between access to WM resources and performance in math tasks (Fürst & Hitch, 2000; Lee & Ng, 2009), these findings suggest that improving WM or updating capacity may also improve children’s academic performance.

**Working memory training and mathematical performance**

To examine if improving WM does indeed lead to improvement in academic performance, we designed a computerized game-based updating intervention programme for children in the Learning Support Programme for Mathematics (LSM). These children are identified
in the first year of formal schooling, and are considered as having mathematical difficulties. The study tested whether the intervention improved WM and whether such improvement had flow-on effects on mathematical performance. The study also compared our intervention programme to an established, but costly, WM training programme: Cogmed. The results showed that training on the Cogmed resulted in short-term improvement on a WM task similar to those used in training. Our intervention programme resulted in better updating capacity at the long-term follow-up, but again only on an evaluation task similar to those used during training. Similar to the extant literature (Dunning, Holmes, & Gathercole, 2013), the findings thus far showed poor transfer to mathematical achievement. This has important implications for continued development of intervention strategies, which we highlight further on in our research plans and recommendations.

**Improving executive functioning and attention**

A study that is currently in progress examines the attentional profiles of students across levels of academic achievement and how attentional skills may interact with intervention. Of particular interest is whether low-achieving students have deficits in specific subsystems of attention (behavioural vs. cognitive; visual vs. auditory; sustained vs. inhibitory control vs. shifting of attention) and whether two interventions—based on recent findings in cognitive science—can help enhance attentional focus in the classroom. If found to be efficacious, teachers may be able to apply such attentional focus aids to help students maintain their attention on learning tasks or inhibit their attention to distractors in class.

Another ongoing study looks at the relationships between sporting activity and EF. Many previous studies have found that both chronic and acute physical activity seem to improve EF in children and adolescents (Best, 2010; Tomporowski, Davis, Miller, & Naglieri, 2008). However, studies did not specifically investigate whether the amount of cognitive engagement in various types of physical activity or exercise could in turn lead to different levels of improved EF performance. We hypothesized that team sports have higher cognitive demands and benefits as compared to more solitary sports such as running (Pellis & Pellis, 2007). We are also investigating
whether this relationship is moderated by the genotype of brain-derived neurotrophic factor (BDNF). Regular exercise has been shown to cause neurogenesis in the hippocampal regions which are associated with learning and memory, through the up-regulation of BDNF (Cotman, Berchtold, & Christie, 2007). However, findings from a recent study suggest that people who carry a particular allele may not benefit cognitively from exercise compared to those who do not (Hopkins, Davis, VanTieghem, Whalen, & Bucci, 2012). It is hoped that our findings will lead to exercise-based EF interventions for low-achieving students who are unresponsive to conventional classroom or cognitive intervention methods.

Development of executive functioning and the establishment of sensitive measures

In a recent study, we examined the development of EF from early childhood to mid-adolescence. Findings showed that amongst 6- to 15-year-olds, EF as measured by various updating/WM, inhibition, and switching tasks was not fully differentiated into separable constructs until 15 years of age. From the age of 6 to 13 years, EF was differentiated into updating and a more general construct that maps onto the inhibitory and switch tasks (Lee et al., 2013). These findings raised important theoretical and methodological implications, and addressed key issues in the field regarding measurement of true latent abilities through sophisticated analytical techniques.

However, these findings, and our recent review of the role of EF in math ability (Bull & Lee, 2014), raised an important question about the sensitivity of some EF measures. For example, although inhibitory abilities are often correlated with academic performance, their explanatory power is typically overshadowed by that of WM and updating. Given the theoretical importance of inhibitory abilities, it is possible that its influence is not fully captured by currently available tasks. Most commonly used inhibition tasks work well in experimental settings but less so when data are subjected to methodology typically deployed in individual differences studies. The development of more sensitive measures of inhibitory abilities will provide researchers with better insight on how changes in inhibitory capabilities affect academic performance. We plan to address this issue in future experimental studies.
Trends in Applied Cognitive Development

Hot and cool executive functioning
Focusing on the interplay between hot and cool EF, a related set of studies at ACDL examined the relationship between trait and state anxiety under different levels of situational stress. One study examined the relative contribution of trait and state test anxiety on children’s task performance using a range of self-report and physiological measures of state anxiety. We also examined whether test-anxious children’s lower processing speed is due to their inability to inhibit attention to task-irrelevant worry. We found that trait test anxiety had a direct detrimental effect on response times in a mental arithmetic task and this effect was not mediated by state test anxiety. Although both self-report and physiological measures of state test anxiety were used, state test anxiety did not emerge as a significant predictor of WM performance. Children who self-reported higher levels of state test anxiety showed poorer skill in inhibiting attention to threat. However, there were no predictive relations between trait and state anxiety with inhibitory ability, and between inhibitory ability and WM performance. Our findings suggest that intervention strategies that relieve the burden of anxiety on WM or improve WM resources will impact positively on performance outcomes of test-anxious children. These include intervention aimed at improving WM-related functions such as cognitive and attentional control (Schmiedek, Lovden, & Lindenberger, 2010), therapeutic interventions that train individuals to develop a disengaging mindset towards worry cognitions (Brown et al., 2011) and study-skills training explicitly targeting study strategies that utilize fewer WM resources (Hayes, MacLeod, & Hammond, 2009).

A related intervention study targeted students’ inhibitory control of attention towards worry cognitions aroused by test anxiety. The study examined the efficacy of a simple relaxation technique—deep breathing—to regulate children’s feelings of anxiety and to enhance performance in test-like situations. Based on previous findings that performance decrements in math-anxious students were mediated by cognitive control in the face of negative arousal (anticipating a math task), the study tested whether deep breathing could improve performance by reducing state test anxiety and improving task focus (enhancing inhibitory control of attention). It was found that taking deep breaths before a test significantly reduced feelings of anxiety and
improved test performance. Findings of this study suggest it may be worthwhile for schools to teach test-anxious children deep breathing—a quick and cost-free tool that can be easily taught and learned.

Another study that examined the interaction between hot and cool EF in learning and performance is our study on the interaction between achievement goals and WM on mathematical performance in children (Lee, Ning, & Goh, 2013). Mastery goals had a direct positive relationship with WM capacity whereas performance goals had direct negative relationship with WM capacity. The negative relation between performance goal and math was stronger for children with lower levels of mastery-goal or WM, than for those with higher levels. These findings suggest that because the availability of WM resources decreases when there are high levels of performance goals—especially those with negative avoidance aspects—such an orientation is associated with poorer mathematical performance. However, high mastery goal levels and WM capacity afford a degree of protection against the detrimental influences of high performance goals. Children with a higher WM capacity did well regardless of their mastery or performance goals.

Future Research Directions and Recommendations
Our laboratory and our colleagues in the Education and Cognitive Development Laboratory (ECDL) have been involved in a number of studies on the interface between cognitive development and education. They are strategically poised to continue with this line of research and will continue to invest in cutting-edge scientific research methods and will further expand into new multidisciplinary areas. There will be a focus on translation, and an emphasis in assisting children with sub-optimal academic performance or cognitive development. This section outlines several key areas for future research and recommendations for links to local educational practice.

Interventions to improve executive functioning
We earlier highlighted that whilst children with poor math skills often have difficulties with WM, training children to better deploy their EF skills (specifically updating) does not necessarily translate into an improvement in mathematical competencies. However, we do not believe this is reason to abandon training of EF skills as a potential
source of intervention for classroom learning. It is possible that direct assessments of EF provide evidence of the individual’s available cognitive capacities, but not how those capacities are used in a classroom setting. This may be better captured by teacher ratings of children’s EF skills as shown in the classroom environment. Furthermore, the updating training may need to be situated in a more ecologically valid context that would make the transfer of their updating skills to classroom tasks a little more explicit.

International findings on the cognitive benefits of co-curricular activities such as music and physical exercise also suggest that research efforts could be expanded to examine the cognitive and self-regulatory effects of these activities. In line with efforts of the Ministry of Education in Singapore to promote the development of the whole child and not just his/her academic abilities, interventions and school practices should not only focus on directly improving cool EF or cognitive abilities but also on the development of cognition-emotional regulation. As direct evidence of the flow-on effects of such intervention on academic performance is still unclear, it is imperative to continue research on the efficacy of such interventions and to explore the cognitive-enhancing benefits and self-regulatory effects of cognitive interventions and other activities.

Finally, policymakers should consider the use of additional non-curricular-based measures of higher cognitive abilities to assess children in schools as the relations between such abilities and academic performance are robust. Instruments that measure WM and other EF provide a finer grained assessment of children’s abilities and learning potential. The use of such instruments may also bring us closer to reducing the pressure of examinations by providing alternative forms of assessment for use in academic decision-making.

Interactive effects of executive functions, attention and emotions on academic performance
Intra-individual, inter-individual and between-groups differences suggest the need to consider cognitive deficits that result from different kinds of inhibitory control (Braver, 2012). One area of work that will
be continued and expanded upon is examining how interactions amongst cool and hot EF (e.g., WM, attention-inhibition and test anxiety) influence learning and performance. Test anxiety, for example, is a non-trivial issue as it can underestimate what children have learned, depressing their performance on aptitude and achievement measures, and limiting their subsequent opportunities in education and career choices. We are planning a follow-up study that builds on our existing work, to further our understanding of the trait anxiety-task performance linkage by examining the role of motivational factors as moderating variables. Drawing on achievement goal theory (Elliot & McGregor, 1999), we want to examine whether individual differences in achievement goal orientations (i.e., the motivational reasons for pursuing achievement tasks) influence the strength of the relationship between test anxiety and task performance.

**Investigating the interaction between cognition and pedagogy**

A related area that should be explored is individual differences in responses to classroom pedagogy or cognitive training. How specific pedagogical innovations improve student learning seems to depend on how students respond to different kinds of approaches. This could be due to multiple contributing variables to learning and cognitive training, such as the interconnection between children’s existing cognitive capabilities, life circumstances, and mental/emotional and physical dispositions. Of interest are the affordances these qualities provide in children’s responses to pedagogy and training, and the resulting changes in both their learning and capacity to learn. A large-scale study is underway to examine the interaction of pedagogy and cognition in kindergarten, as part of a study to document practices across the pre-school sector in Singapore. The study focuses on teacher-child interaction style, in particular emotional support, classroom management and instructional support. Each of these aspects of interaction is thought to be related to particular child outcomes that are critical for school readiness: social-emotional skills, self-regulation, and academic skills. However, children’s response to a certain interactional style will almost certainly also depend on the skills and attributes they have when they first enter kindergarten,
with some more likely to benefit from particular patterns of interaction than others. Our aim in this study is not only to identify best practices in terms of general interaction styles that most generally result in positive child outcomes, but also to evaluate how the child’s attributes on entry to kindergarten interact with pedagogy in the classroom to determine outcomes on entry to primary school.

Understanding the link between cognition and pedagogy is also crucial for ensuring a smooth transition in learning, particularly so for a dynamic subject like math where new and increasingly complex abilities build on previously learned simpler proficiencies. Findings from our previous neuroimaging studies suggest that the model method places less demands on attentional resources and supports the spiral curricular structure if introduced prior to letter-symbolic algebra. This is consistent with current curricular practices. However, findings of interference from the model method highlight the importance of establishing a smooth pedagogical transition. Research looking at the transition from the primary school curricula to secondary school curricula is important as this corresponds to a period in which the structure of EF in children is maturing into the canonical adult structure, as evidenced by findings from our longitudinal studies. At a younger age, the development of fluency in numerical processing (e.g., efficiently moving between non-symbolic, symbolic and verbal-numerical representations, and retrieving simple number facts) is of vital importance; without this the simplest of numerical tasks will require children to engage limited domain-general resources such as WM, leaving little in reserve to deal with the more complex aspects of the task at hand. Research is needed to examine the efficacy of numerical interventions that can help to develop these early skills to ensure a smooth transition from the pre-school to primary school, and to hopefully reduce, or sensitively and specifically identify, children who will require learning support for math.

**Investigating the neurological profiles of children at risk of academic failure**

Future efforts will seek to incorporate recent methodological advances in refining behavioural measures of higher cognitive abilities (such as attention and inhibition) and supplement
behavioural measures with neurophysiological measures. Previous deterrents to using neurophysiological methods such as functional neuroimaging have been their high cost and low ecological validity (e.g., lying still in a scanner). However, recent developments such as fNIRS machines and portable EEG headsets could potentially overcome these concerns. As previously described, behavioural measures alone may not provide a complete picture of children’s cognitive processes. Neurological evidence may help reveal different strategies and resources being used by children with different achievement levels. Such evidence will also be useful in identifying whether children who are performing poorly do so because of underlying cognitive deficits or interactions between cognitive and non-cognitive factors (e.g., home and learning environments, gene and environment interactions, emotion-regulation or personality traits). The implications of such findings include better targeted interventions and a better understanding of why some interventions work, while others do not.

**Thinking and understanding**
An area of emerging interest related to attention and measurement is thinking and understanding. The study of mind wandering as attentional failures has prompted questions on whether task-unrelated thoughts are always counterproductive. It has been argued that spontaneous thoughts may play an important adaptive role in problem solving and learning (Baars, 2010). In the simple act of reading, “elaborative reading is often crucial for maximum comprehension. The challenge is to enable such elaborations to take place without undermining attention to the text.” (Schooler et al., 2004).

Some questions that are important include whether this kind of divided attention is productive and trainable; the relationships amongst mind wandering, incubation, creativity and insight generation, and how these differ from analytical thinking in terms of EF processes; and whether the key to an adaptive or maladaptive mind wandering lies in metacognitive abilities of self monitoring and attention switching. The latter is related to the issue of adaptive or maladaptive multi-tasking—an issue that has generated much recent interest with respect to today’s “multi-tasking” children.
From the laboratory to the classroom

Another area that warrants greater research effort is in translating research findings to the school context. Feasibility studies will be required to test the application of research tools (such as fNIRS or eye-tracking devices) for in-situ classroom research, or pedagogical/classroom interventions and reforms developed out of cognitive developmental research findings. Translating theory to practice will likely be an iterative process. One example is work based on the Cognitive Load Theory (CLT) (Schnotz & Kürschner, 2007; Sweller, 1988; Sweller, Van Merrienboer, & Paas, 1998) which has been highly influential in guiding classroom instructional design in recent decades. Built upon findings of a limited-resource WM system, the theory emphasizes how WM demands of instructional tasks can affect learning. Good instructional designs increase germane load—processing demands contributing to the construction of knowledge schemas—and decrease extraneous load—unnecessary processing demands such as those involving redundant information. Although the current theory is already the result of several updates, continued research efforts will be necessary to take into account advances in the state of knowledge regarding cognitive architecture, such as incorporating the role of EF—currently lacking in the theory.

Conclusions

In this paper, we focused on providing a broad overview of key research conducted locally and internationally. We highlighted the directions in which our future work in applied cognitive development will proceed given current developments in the field, our own interests and core capacity, and the need to address important educational questions in Singapore. These directions generally entail taking our findings from cognitive and developmental psychology and translating them to the classroom environment. This includes an examination of interventions to support the development of both domain-general skills and domain-specific numeracy and math skills, an understanding of individual differences in response to pedagogy and training, and the examination of social-emotional factors (e.g., anxiety) on cognition and learning. Continued collaborative efforts will allow us to address these questions with behavioural, physiological and neurological data and will provide a deeper understanding of the child’s outcomes in response to the pedagogical environment.
References


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