Learning Disabilities: A Contemporary Journal 2 (1), 22–29, 2004

Learning Disability, Intelligence, and Fluid Cognitive Functions of the Prefrontal Cortex: A Developmental Neuroscience Approach

Clancy Blair[1]
Pennsylvania State University

This paper examines the neurobiology of fluid cognitive functions of the prefrontal cortex and considers learning disability as a specific example of a group of developmental disorders characterized by fluid skills impairment in the presence of crystallized intelligence in the normal range. Research indicating fluid cognitive impairments in children with learning disability is reviewed and developmental and measurement implications of these findings are discussed. It is concluded that advances in knowledge of the neurobiology of the prefrontal cortex and in the measurement of fluid cognitive functions can play a central role in progress in learning disabilities research.

This paper examines learning disability from the perspective of developmental neuroscience. Recent neuroscience and neuropsychological research have provided a wealth of knowledge about processes involved in the coordination and control of information in the brain that are essential to effortful learning. Generally speaking, these coordinating processes can be thought of as fluid cognitive functions and as being largely dependent upon areas of the prefrontal cortex working in concert with limbic structures and posterior cortex, including the cerebellum. Increasingly, research has provided evidence of impairments in fluid cognitive functions in individuals with learning disabilities. The purpose of this paper is to review some of this evidence and to examine ways in which knowledge of the neurobiology of these fluid cognitive functions and their role in the learning process can enhance understanding of learning disabilities.

Fluid cognitive functions are those associated with the processing of information in response to novel or to be learned material. Generally speaking these functions include processes related to attention focusing, the inhibition of prepotent or impulsive responding, the maintenance of information in short-term memory, and the coordination of information in the execution of response strategies. As a group, these functions have been defined under terms such as executive function, working memory, or cognitive control (Braver, Cohen, & Barch, 2002; Engle, 2002; Duncan, 2001; Zelazo & Mueller, 2003). Furthermore, although the study of fluid cognitive functions has been accomplished primarily within normative developmental and clinical psychological traditions, these functions are essentially identical to those which have been identified and studied as the fluid component of general intelligence (Gf) within the psychometric individual differences tradition in the study of intelligence (Blair, 2003). Here, fluid intelligence, Gf, has been shown to be distinct from crystallized intelligence (Gc), i.e., knowledge that has been acquired, practiced, and stored over time, with a primary distinction being the automaticity of crystallized knowledge as opposed to the more effortful processing associated with fluid cognitive functions (Gf) (Horn, 1998).

Much of the research effort in the specific study of fluid cognitive functions in learning disability has been within the cognitive developmental tradition. In particular, this work has been guided by the general conceptualization of fluid cognitive skills put forth in the working memory model of Baddeley and Hitch (1994). In this model, working memory is understood to be composed of a central executive and two subsystems dedicated to the maintenance of visual-spatial and verbal-phonological information respectively. Examination of fluid cognition in studies of both reading and math disability have indicated working memory impairments in comparisons with age-matched and to some extent ability-matched (i.e., younger) controls in both the central executive and information maintenance aspects of working memory (Bull & Scerif, 2001; McLean & Hitch, 1999; Sikora, Haley, Edwards, & Butler, 2002; Swanson & Sachse-Lee, 2001).

An overarching goal of research within the fluid cognitive model of Baddeley and Hitch (1994) has been the identification of specific aspects of working memory dysfunction that may be the source of learning deficits for children exhibiting IQ-discrepant achievement in reading and math. Issues that are currently prominent concern the extent to which deficits in the visual-spatial and verbal-phonological subsystems of working memory may be distinct or reflect a single underlying domain general process, and the extent to which working memory deficits may be symptomatic rather than causally related to learning problems (Jarrold, 2001; Swanson, 1999). These issues are critical ones for learning disabilities research for which a developmental neuroscience approach to fluid cognitive skills may be particularly useful. Evidence for distinct subsystems could suggest specific cognitive impairments underlying distinct types of learning problems. At the same time, however, it may be that deficits in one aspect of working memory function beget deficits in other aspects of working memory function and indicate aspects of cognitive function that are symptomatic rather than causally related to learning problems. This paper will discuss the extent to which findings for both domain general and domain specific deficits in learning disability can be seen as consistent with current understanding of the neurological integration of the prefrontally based fluid cognitive system and its relation to general intelligence. Furthermore, it will examine the extent to which knowledge of the developmental neurobiology of fluid cogni-

[1] For correspondence concerning this article please contact. Clancy Blair, 110 Henderson South, University Park, PA 16802. Telephone 814-863-6423, FAX 814-863-6207or email cbb11@psu.edu

tive functions can provide insight into ways in which fluid cognitive dysfunction may be related to learning difficulties both as antecedents and as consequences of learning problems.

Fluid Cognitive Functions and Intelligence. In contrast to the study of working memory and learning disability in the cognitive developmental tradition, the study of learning disability in the psychometric tradition has seen only limited examination of specific patterns of cognitive strengths and weaknesses across the various subtests and second order factors that comprise the general factor of intelligence (Detterman & Thompson, 1997). This is in part due to the very long history of research demonstrating the explanatory power of the general factor of intelligence as well as very clear evidence indicating that in typically developing individuals, fluid cognitive functions of the PFC are highly related to, if not identical with, general intelligence (Gustafsson, 1988; Kyllonen, 1996). Examinations of working memory capacity, an integral component of fluid cognitive functioning, have shown that this aspect of cognition underlies performance on tests widely considered to be good measures of general intelligence (Carpenter, Just, & Shell, 1990; Engle, Tuholski, Laughlin, & Conway, 1999; Kyllonen, 1996). The general capacity constraint in working memory has been associated with measured intelligence in several studies. Specifically, lower measured intelligence is associated with goal neglect in dual task paradigms requiring high working memory load and with reduced learning and performance in a variety of real world learning activities (Duncan, Emslie, Williams, Johnson, & Freer, 1996; Kyllonen & Christal, 1990). Furthermore, evidence from brain imaging research has consistently demonstrated activations in response to working memory tasks in areas of the prefrontal cortex that are the same as those activated by measures of general intelligence (Braver, Cohen, Nystrom, Jonides, Smith, & Noll, 1997; Duncan, Seitz, Kolodny, Bor, Herzog, Ahmed, Newell, & Emslie, 2000). In fact, the higher the g loading of a given cognitive task the greater the PFC activation associated with it, suggesting that the prefrontal cortical system serves as a neural substrate for general intelligence.

More recently, psychometricians have come to recognize limits in the diagnostic utility of the general factor and of specific IQ measures and advocate a cross-battery multi-measure approach that specifically addresses the pattern of performance across various second order factors such as Gf and Gc, as well as other factors such as those associated with visual and auditory perception and processing speed (Flanagan, McGrew, & Ortiz, 2000; McGrew, 1997). As well, although evidence from brain imaging indicates that similar regions of the PFC are recruited in response to diverse fluid cognitive tasks, specific tasks, such as response inhibition or attention switching also tend to demonstrate some unique activations (Duncan & Owen, 2000; Smith & Jonides, 1997; Sylvester, Wager, Lacey, Hernandez, Nichols, Smith, & Jonides, 2003). Determining common and unique brain regions and functions associated with distinct components of fluid cognitive processing should prove valuable in advancing the understanding of relations among brain structure and function and specific learning problems.

Given evidence for strong relations between working memory capacity and performance on measures of general intelligence it would seen without question that the integration of information through prefrontally based cognitive functions is central to human reasoning and problem solving (Duncan, 2001; Miller & Cohen, 2001; Prabhakaran, Narayanan, Zhao, & Gabrieli, 2000). A number of researchers have developed models of intelligence in which fluid skills play a central coordinating role. Woodcock (1998) has generated support for a cognitive performance model in which a fluid thinking skills factor coordinates relations among a crystallized knowledge factor, and short-term memory and processing speed factors. Woodcock's model is similar to, although somewhat more comprehensive than that demonstrated by Engle et al. (1999) in a model of working memory, short-term memory and fluid intelligence. As well, Kyllonen (1996) has generated support for a model of intelligence incorporating working memory, processing speed, and declarative and procedural memory crystallized factors. In confirmatory factor analysis and experimental learning studies examining this model in typically developing individuals, support has been generated for a central role for working memory in the acquisition of knowledge.

Amid this convergence of findings from the study of working memory and psychometric g, however, findings from clinical neuropsychological work provide contravening evidence indicating dissociation of prefrontal fluid cognitive functions and intelligence. Specifically, adults with damage to the dorsolateral PFC perform very poorly on tasks requiring fluid cognitive processing but exhibit measured intelligence within the normal range (Duncan, Burgess, & Emslie, 1995; Waltz, Knowlton, Holyoak, Boone, Mishkin, Santos, Thomas, & Miller, 1999). In fact, individuals with damage to the dorsolateral PFC exhibit scores on measures of fluid IQ one to three standard deviations below their scores on measures assessing primarily crystallized knowledge. Similarly, clinical and experimental studies have shown dissociation between measures of fluid cognitive function and measures of intelligence in a wide range of disorders. Disorders as diverse as autism, ADHD, phenylketonuria, and schizophrenia are all to one extent or another characterized by deficits in fluid cognitive functions but measured intelligence in the normal range (Diamond, Prevor, Callender, & Druin, 1997; Pennington & Ozonoff, 1996; Weinberger, Berman, & Illowsky, 1988; Zelazo & Mueller, 2003). Although there may be some important differences in these dissociations stemming from whether the disorder is acquired or developmental, given evidence for dissociation between fluid functions and measured intelligence in persons with learning disability, it may be that study of dissociation across a variety of disorders can provide insight into a central aspect of human cognitive function and enhance understanding of learning disabilities and their developmental course.

Learning Disability and Fluid Cognitive Function. Given a pattern of evidence in which fluid functions seem integral to intelligence on the one hand, but dissociated from intelligence on the other, one is left wondering what exactly is the relation between fluid functions and intelligence and what are the implications for learning disability? If working memory is central to general intelligence, how can individuals with learning disability exhibit deficits in this aspect of cognitive function but intelligence in the normal range? Here it seems that diverse disorders, including learning disability, suggest something central about human cognitive functioning. Specifically, although fluid and crystallized cognitive functions may seem inextricably intertwined in the typically developing brain, the study of learning disorders indicates that this relation may be less clear than would seem to be indicated by the high correlation among tests of diverse mental abilities represented as pyschometric g. Although fluid and crystallized aspects of intelligence are highly correlated in typically developing individuals, developmental examinations of relations between Gf and Gc have not been necessarily consistent with a single factor theory of intelligence. In fact, in several studies of human cognitive abilities across the lifespan, the Gf-Gc distinction appears to be present early on and the developmental course of diverse cognitive abilities remains distinct (Horn, 1998; Horn & Noll, 1997; McArdle, Ferrer-Caja, Hamagami, & Woodcock, 2002).

However, a central methodological aspect of the dissociation between fluid and crystallized aspects of intelligence concerns the fact that several widely used tests of intelligence, including those frequently used with young children, excel as measures of general mental ability but are weaker as measures of specific cognitive ability factors (Caruso, 2001; Laurent, Swerdlik, & Ryburn, 1992; Woodcock, 1990). Perhaps of most immediate relevance, widely used measures of intelligence for young children disproportionately assess crystallized skills with very limited assessment of fluid cognitive functions (Woodcock, 1990). In extensive factor analyses of the most widely used intelligence batteries for children, including the Wechsler batteries, the Stanford-Binet IV, and the WJ-R among others, Woodcock (1990) and McGrew (1997) have shown that approximately one-third of the batteries' subtests measure crystallized skills and an additional quarter focus on quantitative knowledge and reading/writing skills that directly assess instruction and opportunity for learning. Only approximately 7% of subtests directly assess fluid skills and perhaps another 10% assess processes and memory skills that have a fluid intelligence component.

Given converging evidence for dissociation between fluid and crystallized aspects of intelligence in LD it may be that learning disability is a specific example of a type or category of disorder characterized by intelligence in the normal range but impaired fluid cognitive function. Given that disorders characterized by this pattern of cognitive function are very diverse, with distinct etiologies and phenotypes, the shared distinction of fluid cognitive impairment in the presence of normal intelligence may suggest that a central information processing system in the brain is liable to disruption from myriad factors. And although underlying causes of dysfunction may be distinct, shared behavioral manifestations of dysfunction lead to similarity among diverse disorders. Such equifinality is an intriguing possibility given the ongoing controversy concerning the extent to which IQ-discrepant learning disability (LD) is distinct from age but not IQ discrepant low achievement (LA). Here neurobiological evidence would seem to suggest a clear distinction between learning disability and low achievement. However, this LD-LA distinction has proved contentious in the learning disabilities literature with persuasive reasoning and data presented on both sides of the argument (Algozzine, Ysseldyke, & McGue, 1995; Fletcher et al, 1994; Kavale, 1995; Kavale, Fuchs, & Scruggs, 1994; Pennington, Gilger, Olson, & DeFries, 1992). Examination of the neurobiology of fluid cognitive functions would seem to suggest that although the LD-LA distinction may be real, differentiation among diverse groups of learners for whom the behavioral endpoint is very similar is, of course, going to be very difficult. However, as will be discussed below, examination of the neurobiology of fluid cognitive function may help to indicate why the LD-LA distinction may be a useful one to make..

The Fluid Cognitive System. It is now well established that areas of the prefrontal cortex known to be important for working memory and the regulation of attention are extensively and reciprocally innervated with a wide array of brain areas, including limbic structures and brainstem structures associated with emotional reactivity and autonomic function. In combination, prefrontal, limbic, and brainstem structures integrate cognitive and emotional responses to stimulation (Uylings, Van Eden, de Bruin, Feenstra, & Pennartz, 2000). The primary implication of reciprocal innervation between emotional and cognitive structures in the brain is that prefrontally mediated fluid cognitive functions directly influence and, most importantly for present purposes, are influenced by emotional and autonomic responses to stimulation (Van Eden & Buijs, 2000). A traditional view of reasoning and learning ability as distinct from or liable only to disruption from emotional and autonomic response has been replaced by a model in which cognitive, emotional, and autonomic responses work in concert to organize patterns of response.

The integration of cognitive, emotional, and autonomic responses to stimulation in the PFC is directly relevant to understanding the relation between fluid cognitive functions and early success or difficulty in school (Blair, 2002). Specifically, a corticolimbic circuit integrating dorsolateral, ventromedial, and orbitofrontal areas of the prefrontal cortex with amygdala and hippocampal structures of the interior medial temporal lobe, i.e., the "limbic system", is implicated in fluid cognition (Cohen & Servan-Schreiber, 1992; Davidson, 2002; Weinberger, Berman, Suddath, & Torrey, 1992). In brief, the goal directed behavior associated with functioning of the PFC is dependent in specific ways on activation of the amygdala and hippocampus. For example, the amygdala is integral to the fear response and the establishment of conditioned fear (LeDoux, 1995, 1996). It may also function as a detector of ambiguity and the enhancement of a vigilant state (Whalen, 1998). Such a role is in keeping with evidence that the amygdala directs attention and cognitive processing resources to sources of potential threat for evaluation and execution of response strategies.

The hippocampus is also integral to the information maintenance and inhibitory control functions of the PFC that comprise fluid cognitive functions. Studies of cognitive function in schizophrenic patients have indicated that working memory performance and cerebral blood flow in the dorsolateral prefrontal cortex in response to the Wisconsin Card Sorting Task, a well known and widely utilized measure of PFC function, are highly related to hippocampal volume (Weinberger et al., 1992). In a sample of monozygotic twins discordant for schizophrenia, difference in hippocampal volume between affected and unaffected twins was strongly related to physiological activation in the dorsolateral PFC during the WCST. The greater the within twin pair difference in hippocampal volume, the greater the reduction of physiological activation in the PFC in response to the WCST.

Similarly, computational modeling of the PFC-hippocampus corticolimbic circuit indicates a likely role for the hippocampus in both the maintenance of to be remembered information and the inhibition of competing or interfering information, essential functions of the PFC in fluid cognition. The mechanism by which the hippocampus is thought to perform this function is through the processing of contextual information. Hippocampally dependent representation of context has been demonstrated within the computational model to facilitate the maintenance of competing sets of representations and the emphasizing of task-relevant and the inhibition of task irrelevant processes and information (Cohen & O'Reilly, 1996). Although the maintenance and inhibition functions of the PFC have usually been considered as distinct cognitive processes, within the model, disruption of the hippocampally dependent internal representation of contextual information in a component corresponding to neuromodulatory effects of dopamine in the PFC has been suggested to account for working memory deficits in schizophrenia (Cohen & Servan-Schreiber, 1992). Overall, the activity of dopamine in the PFC is thought to play a central modulatory role in a guided activation theory of PFC functioning and cognitive control of thought and action (Miller & Cohen, 2001).

Furthermore, the goal directed, motivational aspects of prefrontal function have been associated with the ventromedial area of the PFC. Reciprocal connectivity among ventral and dorsolateral PFC and the amygdala constitutes an affective working memory system (Davidson, 2002). This system appears to be central in representing the emotional valence of stimuli and its integrity is essential for holding and acting on information of motivational significance to the organism (Bechara, Tranel, Damasio, & Damasio, 1996). Brain imaging and behavioral studies of the cognitive regulation of emotion and of changes in emotional state have indicated reciprocal PFC cortical-limbic activation (Mayberg et al., 1999; Ochsner, Bunge, Gross, & Gabrieli, 2002). With reappraisal of negative emotion and recovery from sadness and depression, increased dorsolateral prefrontal and decreased limbic activation have been observed. During periods of negative affect without reappraisal, however, increased limbic and decreased prefrontal activations have been observed, providing further evidence for the disruptive role that negative, particularly anxious, emotional experience can have on higher-order processes of attention, memory, and problem solving (Matthews & Wells, 1999).

Relation to Learning Disabilities Research. Evidence indicating the integrated nature of the fluid cognitive system is relevant to learning disabilities research in several ways. For one, the neurobiological evidence suggests interrelatedness of fluid skills processes. A good deal of the emphasis on working memory in LD research has been to isolate distinct aspects of cognitive dysfunction in the learning process. Evidence for problems with the maintenance of information in short-term memory, for problems with inhibitory control processes, and for problems with executive function has been generated (Bull & Johnston, 1997; McLean & Hitch, 1999; Swanson, 1999). Similarly, evidence has been generated for specific fluid cognitive skills deficits in distinct disorders as well as for distinct subtypes within a given disorder (Stanovich, Siegel, & Gottardo, 1997; Willcutt, Pennington, Boada, Ogline, Tunick, Chhabildas, & Olson, 2001). The integrated nature of fluid functions, however, may be one reason why differentiation both between and within specific learning disabilities has been difficult to demonstrate. It is not that differentiation is an unrealizable goal, but that deficits in any one area of functioning are likely to beget observed deficits in other areas. The fluid processing system may be disrupted in different ways for different individuals with the same end result. This would be expected in such a broad and encompassing category such as learning disability. Although one group or sample may have a short-term memory deficit, another may have difficulty with the central executive, with multiple etiologies leading to similar functional endpoints. That is, although the phenotype leading to the categorization of many individuals as having learning problems may be the same, the route by which those individuals end up with that categorization may be very different. Although some might see the breadth of the learning disabilities category as an inherent problem, increasingly, work on the neurobiology of learning would suggest that such breadth is to be expected and that, although difficult, subtyping is a realizable goal (Stanovich et al., 1997).

A good example of equifinality in the etiology of LD is perhaps presented by work indicating that the primary underlying neurobiological impairment for many individuals with LD may not be explicitly related to the forebrain but rather to the hindbrain, namely, the cerebellum (Nicholson, Fawcett, & Dean, 2001). Specifically, the cerebellum is known to play a role in the automatisation of learned skills. As mentioned above, the primary distinction between fluid and cognitive functions concerns the effortful nature of fluid cognition versus the automaticity associated with learned, crystallized knowledge. Problems with the automatisation of letter-sound correspondence, word recognition or basic addition or multiplication knowledge could certainly lead to learning difficulty. In fact, examinations of cerebellar function among learning impaired children and adults have indicated that in a great number of cases, reading difficulty is associated with impairments in balance, motor skills, and other sensory processes known to be associated with cerebellar dysfunction (Nicholson & Fawcett, 1990).

However, not all individuals with cerebellar dysfuntion exhibit learning problems and it may be that in some instances cerebellar problems are a symptom not a cause of learning difficulty. Specifically, it may be that problems with the ordering of information in prefrontally based working memory leads to disruptions in cerebellar functioning. On the other hand, it is equally likely that problems with cerebellar function could lead to problems with fluid cognitive functions, either through an overloaded information flow due to problems with the automatisation of knowledge or through an explicit neurobiological link between cerebellar function and the regulation and ordering of information through prefrontally-based cognitive functions. Research on cognitive impairments associated with cerebellar dysfunction indicate a potentially large role for the cerebellum in coordinating cognitive functions associated with higher order processes such as working memory and inhibitory control, in much the same way that the cerebellum provides the neural foundation of the control and coordination of balance and motor functions (Schmahmann, 1998). Such an integrated and broadly distributed neural system underlying fluid cognitive functions, suggests that impairment at multiple points along the system could lead to similar behavioral endpoints.

Whether involving primarily the forebrain, the hindbrain, or both forebrain and hindbrain, another implication of the integrated nature of the fluid cognitive system for learning disabilities research concerns cognition-emotion relations in learning. Difficulty with cognitive tasks can lead to increased anxiety and stress, which in turn adversely affects the functioning of the very fluid cognitive processes that are needed for learning. As noted above, corticolimbic connectivity between areas of the PFC and limbic structures such as the amygdala serves to limit higher order cognitive processing during times of anxiety and stress (LeDoux, 1995). Although of substantial evolutionary value, such a system can be detrimental to adaptation and learning in individuals with fluid cognitive skills deficits. Here, cognition-emotion reciprocity in the brain may serve as a further limiting factor on learning in children with learning disability and suggests how fluid cognitive deficits might be both a cause and a symptom of learning difficulties. Within such a reciprocal, bidirectional system, motivation and self-efficacy can be increasingly constrained over time, leading to further learning disadvantage and deficits in achievement. Such a role for stress and anxiety in learning problems and in the developing regulation of cognition and emotion has been demonstrated in work on traumatic stress and childhood maltreatment, in which clear evidence for stress related neurobiological impairment in diverse brain areas, including the cerebellum, has been presented (Teicher, Andersen, Polcari, Anderson, Navalta, & Kim, 2003).

Finally, consistent with findings indicating fluid cognitive deficits in the study of learning disability, study of the relation of fluid functions to academic achievement in reading and math in typically developing samples indicates large influence of fluid skills in the early elementary grades with declining influence thereafter (Evans, Floyd, McGrew, & Leforgee, 2002; McGrew & Hessler, 1995). Examination of relations between cognitive ability and academic achievement in the normative sample for the Woodcock-Johnson tests of ability and achievement indicate moderate correlation between fluid skills and achievement in reading and math between age 5 years and age 10 years. In subsequent years, however, crystallized skills predominate and demonstrate large correlations with achievement. Although cross-sectional in design, such data have several implications for assessment and for the early identification of risk for learning disability. Given the large emphasis on the measurement of crystallized intelligence on most currently available and widely utilized tests of cognitive ability in young children, these tests must be seen to have limited diagnostic utility. If the primary predictors of learning in the early elementary grades are fluid skills, then existing intelligence tests will be limited in their ability to identify children at risk for learning problems. Furthermore, these tests will be limited in their ability to differentiate among diverse types of learning problems.

Which is not to say that widely used intelligence tests that are primarily weighted toward crystallized knowledge should be abandoned. On the contrary, as measures of acquired knowledge and other aspects of cognitive function they are invaluable. In particular, as with the cross-battery approach in the psychometric tradition described above, examination of the relation of fluid skills to crystallized and other aspects of intelligence should help in differentiating individuals with learning problems. For example, such comparisons could prove useful for addressing the LD-LA distinction. Fluid deficits in the presence of low levels of performance across a variety of second order factors on intelligence tests might be indicative of LA. In contrast, fluid skills deficits that are dissociated from the pattern of performance on other aspects of intelligence might indicate LD. However, much further study of learning problems is needed and in particular, further work on the measurement of fluid functions and on their relation to existing well established measures of intelligence is needed.

Measurement. There are a number of neuropsychological measures of fluid functions that could be utilized for theoretically motivated examinations of early risk for learning difficulties in young children. These measures assess a wide variety of fluid cognitive functions. For example, the well-known peg tapping task, which assesses inhibitory control in young children, has been validated in a number of studies (Diamond & Taylor, 1996; Diamond, Prevor, Callender, & Druin, 1997). In this task, children are handed a small wooden dowel and asked to tap once when the experimenter taps twice, and twice when the experimenter taps once. After practice trials, children are administered a series of 16 trials in a counterbalanced sequence (8 one tap and 8 two tap trials). The task requires children to inhibit a natural tendency to mimic the action of the experimenter while remembering the rule for the correct response. Normative data indicate that typically developing 3-year-olds exhibit considerable difficulty with the task while by 6 years of age most children perform at ceiling levels. The neuropsychological basis for the task and clinically relevant evidence for impaired performance among children with early and continuously treated phenylketonuria, a condition associated with impaired prefrontal function, have been demonstrated (Diamond et al., 1997). Performance on the peg tapping task has also been positively associated with teacher reported attention in preschool and has demonstrated a positive relation with moderate increase in the stress hormone cortisol, which is know to be important for learning in inhibitory control tasks (Blair & Peters, 2003; Blair, Granger, & Peters, 2003; Davis, Bruce, & Gunnar, 2002).

Similarly, age appropriate variations of category switching tasks such as the Wisconsin Card Sort Task (WCST) (Grant & Berg, 1948) and the recently developed Flexible Item Selection Task (FIST) (Jacques & Zelazo, 2001) are two measures that can be used to assess several aspects of information coordination, planning, and response aspects of fluid function in young children. In these tasks, children are asked to derive categories into which stimulus materials are grouped and then asked to "shift cognitive set" and to group the materials along a new dimension. Evaluation of the number of new categories achieved versus perseveration without shifting set provides an indication of fluid cognitive ability. The neuropsychological basis of the

WCST as a measure of fluid function is well established and serves as a prototypical task through which the FIST and similar sorting tasks are linked to fluid cognitive skills.

Planning and problem solving tasks such as the Tower of London (Shallice, 1982), in which children are presented with colored balls arranged on one of three pegs and asked to complete a target arrangement by moving the balls onto the other pegs in order to match the target, also have an increasingly strong record of application in cognitive research involving children. Children's performance is compared against an optimal sequence of moves that allows for the assessment of planning and the task is thought to draw on planning and problem solving aspects of fluid cognitive function (Welsh, 2002). Furthermore, this measure has been utilized in the study of fluid dysfunction in a number of developmental disorders affecting fluid cognitive functions (Sikora et al., 2002). Normative developmental studies of changes in performance with age on this as well as a number of fluid cognitive tasks are available in Luciana and Nelson (1998) and Welsh (2002).

Although variations on the WCST and Tower of London tasks are perhaps only appropriate for children of school age, the peg tapping and FIST tasks have been successfully utilized with preschoolers. Similarly, delayed response format tasks such as the delayed alternation and A-not-B tasks have been utilized with toddlers and infants. These tasks serve as measures of working memory and inhibitory control in which children observe and retrieve a reward hidden at a particular location. After several trials, the location of the reward is switched to a new location and the child's tendency to perseverate in attempting to retrieve the reward at the old location is assessed. By implementing a delay period between the child's observation of the hiding of the reward and the act of retrieving, the working memory demand of the task can be increased. Normative age trends in the performance of delayed response tasks can be found in Diamond (1990) and Espy, Kaufman, McDairmid, & Glisky (1999).

Although this brief review of some increasingly well established measures of fluid cognitive function is far from comprehensive, it is evident that these measures are of potentially great utility for the early identification of risk for learning problems. A growing body of theory and research in typically and atypically developing populations suggest that these measures may be very relevant to diagnosing and remediating cognitive dysfunction in learning disability. For example, in a comparison of ADHD and reading disability, Willcutt et al. (2001) demonstrated primarily inhibitory control fluid function deficits among individuals with ADHD but working memory deficits in individuals with reading disability. Similarly, in a comparison of children with arithmetic difficulties with children with reading difficulties and those with typical academic achievement, Sikora et al. (2002) produced evidence for impaired performance on the Tower of London task only among children with arithmetic difficulty.

It is likely that increased utilization of measures of fluid cognition in learning disabilities research can play a valuable role in advancing understanding of the causes and consequences of learning problems. However, much further work is required. Most if not all measures of fluid cognitive function have been primarily developed and utilized for clinical populations and there is limited normative data of the type so widely available for measures of intelligence. Furthermore, although there are clearly distinct aspects of fluid cognitive function that these measures are tapping, it is somewhat unclear specifically which functions are being tapped by which measures. Ongoing efforts in adult and child populations to identify distinct components of fluid functions and associated measures of each component, individually or in combination, will provide an increasingly firm basis for the investigation of fluid cognitive deficits in learning disabilities (Miyake, Friedman, Emerson, Witzki, & Howerter, 2000; Pennington, 1997). Certainly, given the potential relevance and utility of these measures, continued measurement development and psychometric work on currently existing measures and the application to learning problems would seem a priority for the field. Advances in our knowledge of the fluid cognitive system and measurement of fluid cognition functioning in early childhood may prove to be a valuable aspect of progress in learning disabilities research over the coming decade.

Dr. Clancy Blair *is assistant professor at the Department of Human Development and Family Studies at Penn State University. His research interests are in child development and public health policies relating to mother and child.*

References

Algozzine, B.,Ysseldyke, J.E., & McGue, M. (1995). Differentiating low achieving students: Thoughts on setting the record straight. *Learning Disabilities Research and Practice, 10,* 140–144.

Baddeley, A.D., & Hitch, G.J. (1994). Developments in the concept of working memory. *Neuropsychology, 8,* 485–493.

Bechara, A., Tranel, D., Damasio, H., & Damasio, A. R. (1996). Failure to respond autonomically to anticipated future outcomes following damage to prefrontal cortex. *Cerebral Cortex, 6,* 215–225.

Blair, C. (2002). School readiness: Integrating cognition and emotion in a neurobiological conceptualization of child functioning at school entry. *American Psychologist, 57,* 111–127.

Blair, C. (2003). *Is EF, Gf?: A developmental neuroscience examination of psychometric and component process approaches to the study of human cognitive abilities.* Manuscript submitted for publication.

Blair, C. & Peters, R. (2003). Physiological and neurocognitive correlates of adaptive behavior in preschool among children in Head Start. *Developmental Neuropsychology.*

Blair, C., Granger, D., & Peters, R. (2003). *Cortisol reactivity is positively related to prefrontal function in preschool children attending Head Start.* Manuscript submitted for publication.

Braver, T.S., Cohen, J.D., & Barch, D.M. (2002). The role of prefrontal cortex in normal and disordered cognitive control: A cognitive neuroscience perspective. In D.Stuss and R. Knight (Eds.), *Principles of frontal lobe function,* (pp. 428–447). New York: Oxford.

Braver, T.S., Cohen, J.D., Nystrom, L.E., Jonides, J., Smith, E.E., & Noll, D.C. (1997). A parametric study of prefrontal cortex involvement in human working memory. *Neuroimage, 5,* 49–62.

Bull, R. & Johnston, R.S. (1997). Children's arithmetical difficulties: Contributions from processing speed, item identification, and short-term memory. *Journal of Experimental Child Psychology, 65,* 1–24.

Bull, R. & Scerif, G. (2001). Executive functioning as a predictor of children's mathematics ability: inhibition, switching, and working memory. *Developmental Neuropsychology, 19,* 273–293.

Carpenter, P.A., Just, M.A., & Shell, P. (1990). What one intelligence test measures: A theoretical account of the processing in the Raven Progressive Matrices Test. *Psychological Review, 97,* 404–431.

Caruso, J.C. (2001). Reliable component analysis of the Stanford-Binet: Fourth edition for 2- to 6-year-olds. *Psychological Assessment, 13,* 261–266.

Cohen, J. D. & O'Reilly, R.C. (1996). A preliminary theory of the interactions between prefrontal cortex and hippocampus that contribute to planning and prospective memory. In M. Brandimonte, G. Einstein, & M. McDaniel (Eds.) *Prospective memory: Theory and Applications* (pp. 267–293). Hillsdale, NJ: Erlbaum.

Cohen, J. D. & Servan-Schreiber, D. (1992). Context, cortex, and dopamine: a connectionist approach to behavior and biology in schizophrenia. *Psychological Review, 99,* 45–77.

Davidson, R.J. (2002). Anxiety and affective style: Role of prefrontal cortex and amygdala. *Biological Psychiatry, 51,* 68–80.

Davis, E.P., Bruce, J., & Gunnar, M.R. (2002). The anterior attention network: Associations with temperament and neuroendocrine activity in 6-year-old children. *Developmental Psychobiology, 40,* 43–56.

Detterman, D.K. & Thompson, L.A. (1997). What's so special about special education? *American Psychologist, 52,* 1082–1090.

Diamond, A. (1990). Developmental time course in human infants and rhesus monkeys, and the neural bases of, inhibitory control in reaching. *Annals of the New York Academy of Sciences, 608,* 637–676.

Diamond, A., Prevor, M.B., Callendar, G., & Druin, D.P. (1997). Prefrontal cognitive deficits in children treated early and continuously for PKU. *Monographs of the Society for Research in Child Development.* Volume 62, No.4, Serial No. 252.

Diamond, A. & Taylor, C. (1996). Development of an aspect of executive control: Development of the abilities to remember what I said and to "do as I say, not as I do". *Developmental Psychobiology, 29,* 315–334.

Duncan, J. (2001). An adaptive coding model of neural function in the prefrontal cortex. *Nature Reviews: Neuroscience, 2,* 820–829.

Duncan, J. Burgess, P., & Emslie, H. (1995). Fluid intelligence after frontal lobe lesions. *Neuropsychologia, 33,* 261–268.

Duncan, J., Emslie, H., Williams, P., Johnson, & Freer. (1996). Intelligence and the frontal lobe: The organization of goal directed behavior. *Cognitive Psychology, 30,* 257–303.

Duncan, J., Seitz, R.J., Kolodny, J., Bor, D., Herzog, H., Ahmed, A., Newell, F., & Emslie, H. (2000). A neural basis for general intelligence. *Science, 289,* 457–460.

Duncan, J. & Owen, A.M. (2000). Common regions of the human frontal lobe recruited by diverse cognitive demands. *Trends in Neurosciences, 23,* 475–483.

Engle, R.W. (2002). Working memory capacity as executive attention. *Current Directions in Psychological Science, 11,* 19–23.

Engle, R.W., Kane, M.J., & Tuholski, S.W. (2001). Individual differences in working memory and what they tell us about controlled attention, general fluid intelligence, and functions of the prefrontal cortex. In A. Miyake & P. Shah (Eds.), *Models of working memory: Mechanisms of active maintenance and executive control* (pp. 102–134). New York: Cambridge University Press.

Espy, K.A., Kaufman, P.M., McDiarmid, M.D., & Glisky, M.L. (1999). Executive functioning in preschool children: Performance on A-not-B and other delayed response format tasks. *Brain and Cognition, 41,* 178–199.

Evans, J.J., Floyd, R., McGrew, K.S., & Leforgee, M.H. (2001). The relations between measures of Cattell-Horn-Carroll cognitive abilities and reading achievement during childhood and adolescence. *School Psychology Review, 31,* 246–262.

Fletcher, J., Shaywitz, S., Shankweiler, D., Katz, L., Liberman, I., Stuebing, K., Francis, D., Fowler, A., & Shaywitz B. (1994). Cognitive profiles of reading disability: Comparisons of discrepancy and low achievement definitions. *Journal of Educational Psychology, 86,* 6–23.

Geary, D.C., Hamson, C.O., & Hoard, M.K. (2000). Numerical and arithmetical cognition: A longitudinal study of process and concept deficits in children with learning disability. *Journal of Experimental Child Psychology, 77,* 236–263.

Grant, D. A. & Berg, E. A. (1948). A behavioral analysis of degree of reinforcement and ease of shifting to new responses in a Weigl-type card-sorting problem. *Journal of Experimental Psychology, 38,* 404–411.

Gustafsson, J-E. (1988). Hierarchical models of individual differences in cognitive abilities. In R. Sternberg (Ed.) *Advances in the psychology of human intelligence: Volume 4* (pp. 35–71). Hillsdale NJ: Erlbaum.

Horn, J. (1998). A basis for research on age differences in cognitive capabilities. In J. McArdle & R. Woodcock (Eds.) *Human cognitive abilities in theory and practice.* (pp. 57–91). Mahwah NJ: Erlbaum.

Horn, J. & Noll, J. (1997). Human cognitive capabilities: Gf-Gc theory. In D. Flanagan, J. Genshaft, & P. Harrison (Eds.), *Contemporary intellectual assessment: theories, tests and issues* (pp. 53–91). New York: Guilford Press.

Jacques, S. & Zelazo, P.D. (2001). The Flexible Item Selection Task (FIST): A measure of executive function in preschoolers. *Developmental Neuropsychology, 20,* 573–591.

Jarrold, C. (2001). Applying the working memory model to the study of atypical development. In J. Andrade (Ed.), *Working memory in perspective,* (pp. 126–150). New York: Psychology Press.

Kavale, K.A. (1995). Setting the record straight on learning disability and achievement: The tortuous path of ideology. *Learning Disabilities Research and Practice, 10,* 145–152.

Kavale, K.A., Fuchs, D., & Scruggs, T.E. (1994). Setting the record straight on learning disability and low achievement: Implications for policymaking. *Learning Disabilities Research and Practice, 9,* 70–77.

Kyllonen, P.C. (1996). Is working memory capacity Spearman's g? In I. Dennis & P. Tapsfield (Eds.), *Human abilities: their nature and measurement* (pp. 49–76). Mahwah NJ: Erlbaum.

Kyllonen, P.C. & Christal, R.E. (1990). Reasoning ability is (little more than) working memory capacity?! *Intelligence, 14,* 389–433.

Laurent, J., Swerdlik, M., & Ryburn, M. (1992). Review of validity research on the Stanford-Binet Intelligence Scale: Fourth edition. *Psychological Assessment, 4,* 102–112.

LeDoux, J. (1995). Emotion: clues from the brain. *Annual Review of Psychology, 46,* 209–235.

LeDoux, J.E. (1996). *The emotional brain.* New York: Touchstone.

Luciana, M. & Nelson, C.A. (1998). The functional emergence of prefrontally-guided working memory systems in four- to eight-year-old children. *Neuropsychologia, 36,* 273–293.

Mayberg, H.S., Liotti, M., Brannan, S.K., McGinnis, S., Mahurin, R.K., et al. (1999). Reciprocal limbic-cortical function and negative mood: Converging PET findings in depression and normal sadness. *American Journal of Psychiatry, 156,* 675–682.

Matthews G. & Wells, W. (1999). The cognitive science of attention and emotion. In T. Dalgleish & M. Power (Eds.) *Handbook of cognition and emotion* (pp. 171–192). West Sussex, England: Wiley.

McArdle, J.J., Ferrer-Caja, E., Hamagami, F., & Woodcock, R. W. (2002). Comparative longitudinal structural analyses of the growth and decline of multiple intellectual abilities over the life span. *Developmental Psychology, 38,* 115–142.

McGrew, K.S. (1997). Analysis of major intelligence batteries according to a proposed comprehensive Gf-Gc framework. In D. Flanagan, J. Genshaft, & P. Harrison (Eds.), *Contemporary intellectual assessment: theories, tests and issues* (pp. 151–180). New York: Guilford Press.

McGrew, K.S. & Hessler, G.L. (1995). The relationship between the WJ-R GF-GC cognitive clusters and mathematics achievement across the life span. *Journal of Psychoeducational Assessment, 13,* 21–38.

McLean, J.F. & Hitch, G.J. (1999). Working memory impairments in children with specific arithmetic learning difficulties. *Journal of Experimental Child Psychology, 74,* 240–260.

Miller, E.K. & Cohen, J.D. (2001). An integrative theory of prefrontal cortex function. *Annual Review of Neuroscience, 24,* 167–202.

Miyake, A., Friedman, N.P., Emerson, M.J., Witzki, A.H., & Howerter, A. (2000). The unity and diversity of executive functions and their contributions to complex "frontal lobe" tasks: A latent variable analysis. *Cognitive Psychology, 41,* 49–100.

Nicholson, R.I. & Fawcett, A.J. (1990). Automaticity: A new framework for dyslexia research? *Cognition, 35,* 159–182.

Nicholson, R.I., Fawcett, A.J., & Dean, P. (2001). Developmental dyslexia: the cerebellar hypothesis. *Trends in Neurosciences, 24,* 508–511.

Ochsner, K.N., Bunge, S.A., Gross, J.J., Gabrieli, J.D.E., (2002). Rethinking feelings: An fMRI study of the cognitive regulation of emotion. *Journal of Cognitive Neuroscience, 14,* 1215–1229.

Pennington, B.F. (1997). Dimensions of executive fintions in normal and abnormal development. In N. Krasnegor, R. Lyon, & P. Goldman-Rakic (Eds.) *Development of the prefrontal cortex: Evolution, neurobiology, and behavior* (pp. 265–281). Baltimore MD: Brookes.

Pennington, B.F., Gilger, J.W., Olson, R.K., & DeFries, J.C. (1992). The external validity of age- versus IQ-discrepancy definitions of reading disability: Lessons from a twin study. *Journal of Learning Disabilities,* 25, 562–573.

Pennington, B.F. & Ozonoff, S. (1996). Executive functions and developmental psychopathology. *Journal of Child Psychology and Psychiatry, 37,* 51–87.

Prabhakaran, V., Narayanan, K., Zhao, Z., & Gabrieli, J.D.E. (2000). Integration of diverse information in working memory within the frontal lobe. *Nature Neuroscience, 3,* 85–90.

Schmahmann, J.D. (1998). Dysmetria of thought: clinical consequences of cerebellar dysfunction on cognition and affect. *Trends in Cognitive Sciences, 2,* 362–371.

Shallice, T. (1982). Specific impairments of planning. In D. E. Broadbent & L. Weiskrantz (Eds.), *The neuropsychology of cognitive function* (pp. 199209). London: The Royal Society.

Sikora, D.M., Haley, P., Edwards, J., & Butler, R.W. (2002). Tower of London performance in children with poor arithmetic skills. *Developmental Neuropsychology, 21,* 243–254.

Smith, E. E. & Jonides, J. (1997). Working memory: A view from neuroimaging. *Cognitive Psychology, 33,* 5–42.

Stanovich, K.E., Siegel, L.S., & Gottardo, A. (1997). Converging evidence for phonological and surface subtypes of reading disability. *Journal of Educational Psychology, 89,* 114–127.

Swanson, H.L. (1999). Reading comprehension and working memory in learning-disabled readers: Is the phonological loop more important that then executive system? *Journal of Experimental Child Psychology, 72,* 1–31.

Swanson, H.L. & Sachse-Lee, C. (2001). Mathematical problem solving and working memory in children with learning disabilities: Both executive and phonological processes are important. *Journal of Experimental Child Psychology, 79,* 294–321.

Sylvester, C. Y., Wager, T., Lacey, S., Hernandez, L., Nichols, T., Smith, E., & Jonides, J. (2003). Switching attention and resolving interference: fMRI measures of executive functions. *Neuropsychologia, 41,* 357–370.

Teicher, M.H., Andersen, S.L., Polcari, A., Anderson, C.M., Navalta, C.P., & Kim, D.M. (2003). The neurobiological consequences of early stress and childhood maltreatment. *Neuroscience and Biobehavioral Reviews, 27,* 33–44.

Uylings, H., Van Eden, C. De Bruin, J. Feenstra, M. & Pennartz, C. (2000) *Progress in Brain Research, Vol. 126, Cognition, emotion and autonomic responses: The integrative role of the prefrontal cortex and limbic structures.* Amsterdam: Elsevier.

Van Eden, C.G. & Buijs, R.M., (2000). Functional neuroanatomy of the prefrontal cortex: autonomic interactions. In H. Uylings, C. Van Eden, J. De Bruin, M. Feenstra, & C. Pennartz (Eds.) *Progress in Brain Research, Vol. 126, Cognition, emotion and autonomic responses: The integrative role of the prefrontal cortex and limbic structures.* (pp. 49–62). Amsterdam: Elsevier.

Waltz, J.A., Knowlton, B.J., Holyoak, K.J., Boone, K.B., Mishkin, F.S., Santos, M., Thomas, C.R., & Miller, B.L. (1999). A system for relation reasoning in the human prefrontal cortex. *Psychological Science, 10,* 119–125.

Weinberger, D.R, Berman, K.F., & Illowsky, B.P. (1988). Physiological dysfunction of the dorsolateral prefrontal cortex in schizophrenia. III. A new cohort and evidence for a monoaminergic mechanism. *Archives of General Psychiatry, 45,* 609–615.

Weinberger, D. R., Berman, K. F., Suddath, R., & Torrey, E. F. (1992). Evidence of dysfunction of a prefrontal-limbic network in schizophrenia: a magnetic resonance imaging and regional cerebral blood flow study of discordant monozygotic twins. *American Journal of Psychiatry, 149,* 890–897.

Welsh, M.C. (2002). Developmental and clinical variations in executive functions. In D. Molfese and V. Molfese (Eds,) *Developmental variations in learning: Applications to social, executive function, language, and reading skills* (pp. 139–185). Mahwah NJ: Erlbaum

Whalen, P.J. (1998). Fear, vigilance, and ambiguity: Initial neuroimaging studies of the human amygdala. *Current Directions in Psychological Science, 7,* 177–188.

Willcutt, E.G., Pennington, B.F., Boada, R., Ogline, J.S., Tunick, R.A., Chhabildas, N.A., & Olson, R.K. (2001). A comparison of the cognitive deficits in reading disability and attention-deficit/hyperactivity disorder. *Journal of Abnormal Psychology, 110,* 157–172.

Woodcock, R.W. (1990). Theoretical foundations of the WJ-R measures of cognitive ability. *Journal of Psychoeducational Assessment, 8,* 231–258.

Woodcock, R.W. (1998). Extending Gf-Gc theory into practice. In J. McArdle & R. Woodcock (Eds.) *Human cognitive abilities in theory and practice* (pp.137–156). Mahwah NJ: Erlbaum.

Zelazo, P. D., & Muller, U. (2003). Executive function in typical and atypical development. In U. Goswami (Ed.), *Handbook of Childhood Cognitive Development.* Oxford: Blackwell.