

# How similar are fluid cognition and general intelligence? A developmental neuroscience perspective on fluid cognition as an aspect of human cognitive ability

**Clancy Blair**

Human Development and Family Studies, Pennsylvania State University,  
University Park, PA 16802-6504  
cbb11@psu.edu

**Abstract:** This target article considers the relation of fluid cognitive functioning to general intelligence. A neurobiological model differentiating working memory/executive function cognitive processes of the prefrontal cortex from aspects of psychometrically defined general intelligence is presented. Work examining the rise in mean intelligence-test performance between normative cohorts, the neuropsychology and neuroscience of cognitive function in typically and atypically developing human populations, and stress, brain development, and corticolimbic connectivity in human and nonhuman animal models is reviewed and found to provide evidence of mechanisms through which early experience affects the development of an aspect of cognition closely related to, but distinct from, general intelligence. Particular emphasis is placed on the role of emotion in fluid cognition and on research indicating fluid cognitive deficits associated with early hippocampal pathology and with dysregulation of the hypothalamic-pituitary-adrenal axis stress-response system. Findings are seen to be consistent with the idea of an independent fluid cognitive construct and to assist with the interpretation of findings from the study of early compensatory education for children facing psychosocial adversity and from behavior genetic research on intelligence. It is concluded that ongoing development of neurobiologically grounded measures of fluid cognitive skills appropriate for young children will play a key role in understanding early mental development and the adaptive success to which it is related, particularly for young children facing social and economic disadvantage. Specifically, in the evaluation of the efficacy of compensatory education efforts such as Head Start and the readiness for school of children from diverse backgrounds, it is important to distinguish fluid cognition from psychometrically defined general intelligence.

**Keywords:** cognition; cognition-emotion reciprocity; developmental disorders; emotion; fluid cognition; Flynn effect; general intelligence; limbic system; neuroscience; phenylketonuria; prefrontal cortex; psychometrics; schizophrenia

## 1. Introduction

### 1.1. What is general intelligence?

Historically, theories of intelligence have focused on the identification of a single factor, referred to as *psychometric g*, that has been shown to underlie performance on tests of mental abilities (Spearman 1927). The single-factor theory reflects the fact that the various subtests of IQ measures correlate positively. Although several alternative interpretations exist as to just what this positive manifold among tests means, it is beyond question that a single mathematically derived factor can be extracted from tests of diverse mental abilities (Carroll 1993; Jensen 1998; see the edited volume by Sternberg & Grigorenko 2002). Jensen (1998) provides a comprehensive review of research on *g*, detailing the evidence for *g* and the relation of *g* to various real-world outcomes by using the method of correlated vectors. There are, however, numerous questions about *g* that are the subject of ongoing research and scientific exchange. In particular, questions about the unitary nature of *g*, the

biological bases of *g*, and the extent to which *g* is itself reducible to known, theoretically tractable cognitive processes, are interrelated, overarching questions high on the priority list for intelligence researchers.

As a mathematically defined entity with large explanatory power, the general factor has been pervasive in the psychological literature for over one hundred years. However, it is important to keep in mind that

CLANCY BLAIR, Ph.D., M.P.H., is an Associate Professor in the Department of Human Development and Family Studies at Pennsylvania State University. He is the author of numerous peer-reviewed publications examining the effects of early psychosocial adversity on child health and development. His chief interest concerns the interrelation of cognitive and emotional development early in the life course, and the ways in which neurobiology and experience interact to shape developmental trajectories in early childhood.

psychometric  $g$  is not a thing in itself but a manifestation of some as yet undefined properties of brain structure and function. In fact, it is only in the last several decades that the underlying processes and functions through which  $g$  may be manifest have begun to be worked out in any detail, albeit with only limited success. For example, a general speed-of-processing hypothesis has been examined using measures of inspection time and reaction time. Although the conceptual relation of these measures to  $g$  is sound, a number of studies have shown that their empirical relation to  $g$  tends to be small (Crawford et al. 1998; Luciano et al. 2004). Similarly, a conceptually sound general synaptic plasticity thesis has been proposed as an underlying basis for  $g$  (Garlick 2002). However, although perhaps promising, the synaptic plasticity argument lacks specificity as to a clear relation between brain plasticity and intelligence and at present offers no way of measuring individual differences in plasticity that might correlate with psychometric  $g$ .

In apparent contrast to general speediness and plasticity explanations for  $g$ , work on fluid cognitive functions – those associated with general reasoning and problem-solving processes and referred to primarily as *working memory* (WM), *executive function* (EF), or *fluid intelligence* (gF) – seems to have shown some early and substantial promise in indicating that both the conceptual basis and neural structural basis for  $g$  may be close at hand. However, as is argued in section 3 and the sections that follow, this promise is perhaps more apparent than real. Given psychometric evidence for a relation between fluid cognition and psychometric  $g$  and the increasingly well-established neural basis for this relation, what has yet to be thoroughly examined is the growing body of evidence indicating that fluid cognitive functions are in some instances clearly dissociated from general intelligence. Evidence indicating dissociation of fluid cognitive functions from other aspects of  $g$  is something of a problem for research on human cognitive abilities because it calls into question some earlier conclusions and prior thinking about the general factor. In particular, dissociation of fluid cognitive functions from other indicators of mental abilities through which  $g$  is manifest suggests that some reconceptualization of human cognitive competence is needed and may indicate instances in which  $g$  has reached or exceeded the limits of its explanatory power.

Plainly stated, the central thesis of this target article is that currently available evidence indicates that, although fluid cognition appears highly similar to general intelligence in many instances, the association between fluid function and general intelligence is limited in ways that are important for understanding the development of cognitive competence in humans and its application across the lifespan. Furthermore, once the limits of the association between fluid cognition and  $g$  are recognized, the independent fluid cognitive construct can be seen to have a relevance to human behavior that may be as far reaching in its explanatory power, if not more so, than that associated with psychometric  $g$ . However, the limits of the association between fluid cognition and general intelligence may be most pronounced in populations in which specific environmental and/or genetic background factors are distinct from those of normative or typically developing populations. These instances help to “pull apart” fluid cognition and  $g$ , whereas ordinarily these

two aspects of functioning covary to an extent that they appear to be unitary. Overall, the available evidence suggests that fluid cognition is an aspect of cognitive functioning that can be under considerable environmental influence both cumulatively over time and interactively within context in a way that indicates it to be a highly salient influence on behavior, but one that is distinct from general intelligence, psychometrically defined.

Several sources of evidence indicate dissociation of fluid cognition from  $g$ , and the purpose of this target article is to review this evidence and to consider its implications for understanding cognition and human behavior. The first source of evidence is psychometric and at the population level of analysis and concerns the worldwide rise in the mean level of mental test performance known as the *Flynn effect*. The second is neuroscientific and at the individual level and concerns evidence indicating fluid cognitive and learning impairments in humans and in animals with damage to a neural network integrating areas of the prefrontal cortex with structures of the brain’s limbic region. A third source of evidence is neuropsychological and concerns the extent to which cognitive impairments in identified developmental disorders are consistent with a pattern of dissociation between fluid cognitive functions and general intelligence. Having considered this evidence, work examining reciprocal interconnectivity among limbic brain structures associated with emotional reactivity and the stress response and prefrontal cortical structures associated with fluid cognition is reviewed. It is argued that this work indicates potentially large environmental influence on fluid functioning and thereby on aspects of cognition that many have previously taken to be central to general intelligence. In summary, it is suggested that evidence outlining environmental influence on fluid cognition may provide for an important advance in understanding the development of human cognitive ability.

## 2. Fluid cognition

### 2.1. What is fluid cognition?

*Fluid cognitive functioning* can be thought of as all-purpose cognitive processing not necessarily associated with any specific content domain and as involving the active or effortful maintenance of information, whether verbal or visual-spatial in working memory for purposes of planning and executing goal directed behavior (Baddeley 1986; Kane & Engle 2002). As a consequence, fluid functioning involves the inhibition of irrelevant, competing, or prepotent information likely to interfere with information maintenance and response execution and the alternate shifting and sustaining of attention important for organizing and executing sequential steps or actions. Furthermore, fluid functioning is for the most part distinguishable from cognitive functioning associated with previously acquired knowledge available in long-term store, referred to as *crystallized intelligence* (gC). It is important, however, not to overstate the distinction between fluid processes and other aspects of cognition or the overall unity of the processes that comprise fluid functioning. Fluid functions play some role in encoding and retrieving crystallized knowledge in long-term store (Braver et al. 2001; Ranganath et al. 2003), and although the overlap among information maintenance,

attention shifting, and interference resolution processes in completing complex tasks is considerable, these aspects of fluid cognition are distinguishable (Miyake et al. 2000) and associated to some extent with distinct patterns of brain activation as observed by using brain-imaging techniques (Smith & Jonides 1997; Sylvester et al. 2003). As a unitary entity, however, fluid function has been described in the psychological literature under a variety of terms, including executive function, executive attention, effortful control, and working memory capacity. Although researchers may emphasize one or another aspect of fluid functioning under the various terms, each essentially describes the same overarching construct, and for the remainder of this article the term *fluid cognitive functioning* is utilized as a primary descriptor for these integrated aspects of cognition and is used interchangeably to some extent with the terms working memory and executive function.

### **2.2. Association between fluid cognition and general intelligence: Psychometric evidence**

As domain general indicators of integrated cognitive processes involving information maintenance, attention shifting, and resistance to interference, measures of fluid cognition have not surprisingly demonstrated substantial relations with performance on measures of general intelligence (Embretson 1995; Engle et al. 1999b; Gustafsson 1984; 1988; Kyllonen & Christal 1990). Factor-analytic studies have demonstrated that measures of working memory correlate extremely highly ( $r$ 's > 0.90) with the general factor extracted from various measures of cognitive ability (Colom et al. 2004; Gustafsson 1988; Kyllonen 1996), and fluid functions have been shown in latent variable models to be essential aspects of general intelligence (Conway et al. 2003; Kane & Engle 2002; Süß et al. 2002). Tests that directly measure fluid cognitive functions have higher  $g$  loadings than do other cognitive measures (i.e., they exhibit larger factor scores on the higher-order  $g$  factor extracted from hierarchical analysis of mental test batteries; see Colom et al. 2004; Gustafsson 1984; 1988). And *working memory capacity*, defined as the amount of information that can be actively maintained in the presence of conflicting or distracting information, has been shown to underlie performance on a variety of tests of mental abilities, including measures of general intelligence (Carpenter et al. 1990; Engle et al. 1999b; Kyllonen & Christal 1990).

### **2.3. Association between fluid cognition and general intelligence: Evidence from brain imaging**

Furthermore, not only do psychometric data indicate the centrality of fluid cognition in the study of general intelligence (e.g., Engle et al. 1999b; Süß et al. 2002), studies examining brain structures and neural interconnectivity that support fluid cognitive functions (Braver et al. 1997; MacDonald et al. 2000; Smith & Jonides 1997) indicate a high degree of overlap within the brain between fluid cognition and general intelligence (Duncan et al. 2000; Prabhakaran et al. 1997; Thompson et al. 2001). Structural magnetic resonance imaging (MRI) has indicated positive correlations between IQ and gray matter in the prefrontal cortex (PFC) and anterior cingulate cortex (ACC) and has

shown frontal gray matter, as with IQ, to be highly heritable (Thompson et al. 2001; Wilke et al. 2003; but see Haier et al. 2004 for evidence indicating a more distributed structural neural basis for intelligence). And functional brain imaging has consistently demonstrated activations in dorsolateral areas of the PFC in response to working memory tasks that are highly similar to activations observed in response to measures of general intelligence such as Raven's Progressive Matrices Test (Duncan et al. 2000; Prabhakaran et al. 1997). By demonstrating increasing PFC activation with parametric increase in the working memory load or cognitive control demand of tasks performed during imaging, these studies have linked the PFC to fluid cognition (Braver et al. 1997; MacDonald et al. 2000; Rypma et al. 1999) and present an apparent neurocognitive basis for general intelligence (Duncan et al. 2000; Gray et al. 2003).

Using positron emission tomography, brain activation in dorsolateral PFC, and to some extent ACC, has been selectively associated with high  $g$  cognitive tasks (Duncan et al. 2000). Furthermore, PFC activation in response to diverse tasks has indicated that the integration of information in working memory, such as verbal and spatial information, or maintenance of information in working memory while executing subsidiary tasks (i.e., cognitive control functions that would seem to be the hallmark of general intelligence), is associated with greater PFC activation than that associated with either task on its own (Koechlin et al. 1999; Prabhakaran et al. 2000). Furthermore, study of individual differences in intelligence and activation in the PFC by using functional magnetic resonance imaging (fMRI) found performance on Raven's matrices test to be positively correlated with individual level of left lateral PFC activation in response to the 3-back condition of an  $n$ -back working memory task (Gray et al. 2003).

The relation between activation in the PFC and performance on working memory tasks and tests of intelligence, however, is not one such that greater activation necessarily equals higher performance. Examinations of individual differences in working memory capacity indicate higher levels of PFC activation at moderate working memory loads in adults with limited working memory capacity relative to adults with greater working memory capacity. Change in activation in the PFC in response to increasing working memory load demonstrates an inverted U shape with increasing activation at initial load levels followed by decreasing activation once a capacity set point is exceeded (Callicott et al. 1999; Goldberg et al. 1998; Rypma et al. 1999). Increased frontal activation in individuals with lower working memory capacity appears to reflect processing inefficiency in the PFC and is similar to the finding of an inverse relation between cerebral glucose metabolism and IQ as reported by Haier (1993; see also Haier et al. 2003).

Increased PFC activation as observed in imaging studies of brain activation in response to measures of general intelligence reflects the curvilinear relation between PFC activation and working memory load, indicating relative activation at high working memory load. For example, in the study by Gray et al. (2003), the relation between change in PFC activation and intelligence was observed only in the high working memory load 3-back condition of the task. Furthermore, this relation was specific to

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trials in which attention and inhibition demand was very high because of the presence of lure stimuli (i.e., recently viewed stimuli in the 2-, 4-, or 5-back position). In the study by Gray et al., individuals exhibiting higher left lateral PFC activation in this highly demanding 3-back “lure trial” condition tended to score higher on Raven’s matrices test.

Experimental and brain-imaging research strongly suggests that fluid cognitive processes of the PFC play a prominent role in higher-order cognition and that the brain structures and neural interconnectivity that support fluid functions may serve as the neural substrate for general intelligence. It is important not to map cognitive functions directly onto specific cortical areas, however, but to recognize the distributed nature of certain types of information processing in the brain in which the PFC and ACC may play central roles (Carpenter et al. 2000; Cohen et al. 1997). For example, brain-imaging studies of working memory and fluid intelligence have observed temporal, parietal, occipital, and cerebellar activations in addition to activation in distinct regions of the PFC (Cabeza et al. 2002; Duncan et al. 2000; Gray et al. 2003; Prabhakaran et al. 1997). Structural MRI has also indicated relations between IQ and brain volumes in parietal, occipital, and temporal as well as frontal cortical areas (Haier et al. 2004). Furthermore, studies of cognitive impairment associated with cerebellar dysfunction, in particular, indicate a potentially large role for the cerebellar vermis in coordinating fluid cognitive functions (Teicher et al. 2003), in much the same way that the cerebellum provides a neural foundation for the coordination of balance and movement (Schmahmann 1998). And examinations of the role of limbic structures in fluid cognition, particularly the hippocampus, as reviewed in section 5, but also the thalamus (Van der Werf et al. 2000; 2003), indicate prominent roles for these brain structures in tasks associated with prefrontal cortical activity.

Furthermore, the PFC is not a unitary entity but is composed of distinct areas. Although dorsolateral areas of the PFC have been primarily associated with working memory and general intelligence (Duncan et al. 2000), imaging studies of working memory indicate lateralized activations associated with verbal versus visual-spatial types of information and information updating and more ventral medial activations associated with information maintenance (Cohen et al. 1997; Rypma et al. 1999; Smith et al. 1996). Also, orbitofrontal and ventral medial areas of the PFC are associated with performance on fluid cognitive tasks that involve some reward component or in which some positive or negative emotion is evoked (Davidson 2002). Similarly, studies employing fMRI have demonstrated activation in the ACC to be associated with error detection and performance-monitoring processes (Bush et al. 2000; MacDonald et al. 2000) and, most significantly for present purposes, have demonstrated the ACC to be comprised of cognitive and emotional divisions that interact reciprocally in response to specific types of information (Bush et al. 2000). Overall, evidence for relations between areas of the PFC and ACC and specific aspects of cognition and emotion suggest that a variety of influences, particularly those associated with emotional arousal and the stress response, may impact fluid cognitive functioning and its apparent similarity to general intelligence.

### **3. Fluid cognition and general intelligence: Evidence for dissociation in adults**

#### **3.1. Evidence from the Flynn effect: Rising mean IQ and dissociation of fluid skills and general intelligence**

Caveats about whole brain processing and the role of diverse brain structures in studies of working memory and general intelligence are more than just gentle reminders to think broadly about brain function and mental ability. Although brain-imaging and psychometric findings present a striking convergence of evidence seemingly in support of a fluid cognitive basis for general intelligence, a number of sources provide contravening evidence indicating that fluid skills cannot be *g*. Most prominent, perhaps, is the rapid secular rise in IQ over the past century known as the Flynn effect (Flynn 1984; 1987; 1999). Flynn’s examinations of IQ gains have indicated that gains are particularly large, in fact, massive, on tests of fluid skills. Most noteworthy is the finding that gains are greatest, upward of 18 points in a single generation, on Raven’s Progressive Matrices Test, a test previously thought to be a relatively pure measure of psychometric *g* and, as already noted, one that is highly dependent on fluid cognition and the integrity of the PFC. Mean IQ gains on measures more closely tied to crystallized intelligence, however, are considerably smaller and become increasingly small the closer intelligence subtests come to measuring purely crystallized aspects of cognition. The very rapid and substantial rise in scores on measures of fluid intelligence without a concurrent rise of similar magnitude in crystallized skills suggests dissociation of fluid cognitive functions from *g*.

The indication of change in fluid skills independent of *g* has been further substantiated by analysis of measurement invariance in data from successive normative cohorts on a variety of intelligence tests (Wicherts et al. 2004). Gains in IQ on each of the tests examined could not be accounted for by increases in the common factor, *g*, but were shown to reflect systematic sources of variance between normative cohorts in specific subtests. However, not all observed gains were in the fluid realm of cognition; gains were also observed in crystallized content. And not all fluid subtests demonstrated gains. Furthermore, decreasing scores were observed in some cohorts, although these decreases were primarily among recent cohorts and associated with crystallized knowledge. At the very least, the analysis clearly lends itself to the conclusion that intelligence tests are not measurement invariant between cohorts and that, while some increase in general intelligence appears to have occurred, change associated with rising mean IQ is, by and large, subtest specific.

The historical data on mean increases in IQ strongly suggest the presence of environmental influences on fluid cognitive skills that led to a rise in fluid cognition independent of *g*. As mean increases have occurred too rapidly to be attributable to genetic selection, it is clear that increases in IQ as measured by several widely used tests of intelligence most likely reflect social changes that impacted specific cognitive functions associated with performance on specific measures. As noted by Flynn (1999), if the change were in the general factor, this would indicate a mean level of cognitive functioning in entire

cohorts of prior generations that is in the range of mental retardation. However, this is clearly not the case and indicates that increases in fluid cognitive abilities between generations must have specific determinants and be selectively associated with distinct outcomes. Accordingly, any satisfactory explanation for the rise in fluid skills relative to crystallized skills would seem to need to identify mechanisms that could so greatly affect one aspect of intelligence over the other. While most explanations for rising mean IQ tend to be underspecified on this point (i.e., general increases in parenting skill, education, or nutrition), others that more directly address the types of skills tested for in measures of fluid intelligence (such as increased visual-spatial complexity or selective changes in specific aspects of education associated with fluid-skills development) are perhaps more likely to be shown to account for the phenomenon (Dickens & Flynn 2001b; Williams 1998). Whatever the case, the data on rising mean IQ clearly suggest that conclusions about the relation between fluid cognition and *g* are in need of some revision.

### **3.2. Clinical evidence: Dissociation of fluid skills and general intelligence**

As with the Flynn effect but at the individual rather than population level, findings from clinical neuropsychological work provide further evidence indicating dissociation of prefrontally based fluid cognitive functions from general intelligence. Here, with the emphasis on a decrease rather than a rise in fluid intelligence, adults with damage to the dorsolateral PFC perform very poorly on fluid cognitive tasks but exhibit measured general intelligence within the normal range (Duncan et al. 1995; Waltz et al. 1999). In fact, individuals with damage to the dorsolateral PFC exhibit scores on measures of fluid intelligence that are one to three standard deviations below their scores on measures assessing primarily crystallized intelligence. Such data can easily be taken, and have been previously by many, as support for what would seem to be the erroneous conclusion that prefrontally based fluid skills are unrelated to intelligence! However, adult patients with lesions to the PFC demonstrate intact IQ relative to matched controls as assessed by the Wechsler Intelligence Scale for Adults (WAIS) while simultaneously exhibiting substantial postmorbid fluid-intelligence deficits as measured by the Cattell Culture Fair Test (Duncan et al. 1995). In essence, whereas the crystallized IQ of these individuals is in the normal range, fluid IQ scores are in the range of mental retardation. No such discrepancy is observed among matched controls who, in fact, exhibit fluid-intelligence scores equivalent to or higher than their WAIS scores. Further examination of the deficit displayed on measures of fluid IQ in patients with frontal lesions but intact IQ as assessed by the WAIS indicates that performance is dramatically impaired by the requirement of holding multiple relations in mind simultaneously when attempting to solve problems adapted from Raven's matrices test. Individuals with prefrontal damage exhibit no deficits on problems whose solution requires holding in mind no relations or only one relation, but exhibit a near inability to solve problems involving two or more relations (Waltz et al. 1999).

Although seemingly contradictory, given the apparent relation between fluid cognition and general intelligence in typically developing populations, these fascinating results become remarkably clear in light of the fact that the WAIS, perhaps more than any other widely used measure of intelligence, disproportionately assesses crystallized intelligence (Ashton et al. 2001; McGrew 1997). Implications of the discrepancy observed by Duncan et al. (1995) and Waltz et al. (1999) for understanding intelligence and what it is that intelligence tests measure, however, are far from clear. Duncan et al. reason that perhaps the WAIS represents knowledge already acquired and therefore intact, whereas tests of fluid intelligence represent skills through which crystallized knowledge was acquired in the past and further knowledge would be acquired in the future. However, their data cannot readily address such an interpretation. For one, there would need to be some indication that the ability to acquire new types of crystallized information is dramatically impaired in patients with frontal lesions. Duncan et al.'s interpretation is speculative, and their data are not longitudinal and can offer no insight into the developmental relation between fluid and crystallized skills. However, there are data available to address this important point and the following sections examine the viability of such a developmental hypothesis.

## **4. Fluid cognition and general intelligence: Evidence for dissociation in children**

### **4.1. Developmental evidence: Typical development**

The idea that fluid intelligence (*gF*) precedes or paves the way for the development of crystallized intelligence (*gC*) is not new. Cattell and Horn, the originators of the *gF-gC* theory of intelligence, proposed several reciprocal developmental relations between fluid and crystallized intelligence (Cattell 1971; Horn & Cattell 1967). Cattell and Horn theorized that *gF* would be a precursor to *gC* because fluid skills would facilitate and enhance the acquisition of crystallized knowledge. Limited examinations of this investment hypothesis, however, have failed to provide strong support for a directional relation between *gF* and *gC*. Similarly, the authors hypothesized that the *gF-gC* distinction would not be prominent in young children. As with the body of research examining change in diverse cognitive abilities in the study of cognitive aging, however, the *gF-gC* distinction is present early in the life span and the developmental course of diverse cognitive abilities remains distinct (Horn & Hofer 1992; Horn & Noll 1997; McArdle et al. 2002). Analysis of intellectual abilities from age 2 to 95 years in an accelerated longitudinal design with the Woodcock-Johnson Psycho-Educational Battery-Revised (WJ-R) found that "the functions describable as broad fluid reasoning (*gF*) and acculturated crystallized knowledge (*gC*) are separable entities that have different growth patterns" (McArdle et al. 2002, p. 134). Distinct patterns hold for several distinguishable aspects of cognitive ability across the life span. Furthermore, rates of change noted by McArdle et al. (2002) are particularly rapid in early childhood such that change in fluid skills over a single year in childhood is equivalent to change over an 11-year span in adulthood. For crystallized skills, change over a single year in

childhood is equivalent to change over the entire adult life span.

The gF-gC distinction has also been prominent in the study of cognitive aging for some time as evidenced by the relatively greater stability in crystallized as opposed to fluid function (Schaie 1994). Neurobiological evidence suggests that fluid decline with age is associated with alterations in the neurobiology of the PFC and reduced efficiency in processing of information in the PFC (Braver & Barch 2002; Cabeza et al. 2002; West 1996). As with neurobiological evidence in research on cognitive aging, it is likely that influences on the neurobiology of the PFC also play some role in the development of fluid cognition independent of general intelligence early in the life span. However, life-span analysis examining differentiation of cognitive abilities at different ages, while indicating general differentiation in all age groups, indicates that gF-gC correlation is somewhat larger among the very young and the very old (Li et al. 2004), perhaps suggesting some directional relation of gF to gC at the extremes of the life span. Alternatively, it may be that fluid cognition plays a particularly important role in intelligence-test performance in the very young and the very old and, for this reason, gF and gC appear more highly related in these age groups.

In contrast to research on cognitive aging, however, the examination of the gF-gC distinction in children has not been extensive. The reason could be that relations between IQ and fluid cognition labeled as executive function (EF) or working memory are not strong given the limited assessment of gF currently available in many widely used intelligence tests (Woodcock 1990). The study of fluid function under the label of EF in children, however, is a rapidly growing area of research in which the definition of EF employed is essentially identical to that used by individuals studying working memory and intelligence in adults. Specifically, when cognitive researchers working with child populations define EF as the maintenance of an appropriate problem-solving set involving mental representation of a given task and goal state within a limited-capacity central processing system (Welsh & Pennington 1988), they are describing cognitive processes that are being studied under the name of working memory in adults (e.g., Carpenter et al. 1990; Conway et al. 2002; Prabhakaran et al. 1997; 2000). The few studies examining the relation of measures of working memory and EF to measures of intelligence in typically developing children have indicated some overlap between fluid skills and intelligence as well as unique variance in school achievement associated with each. For example, whereas one study identified substantial overlap between measures of working memory and gF measured by Raven's matrices test (de Jong & Das-Smaal 1995), a finding highly similar to the adult literature (Engle et al. 1999b), another found that EF tasks predicted unique variance in math achievement over and above that associated with a widely used estimate of Wechsler full-scale IQ (Bull & Scerif 2001). Here again, because of the underrepresentation of fluid skills in the Wechsler batteries, use of the Wechsler would be expected to result in unexplained variance associated with EF measures. Furthermore, and perhaps most interesting for present purposes, factor-analytic examinations of various EF tasks have demonstrated that the tasks are largely unrelated to performance on measures of

intelligence assessing primarily crystallized knowledge (Espy et al. 1999; Krikorian & Bartok 1998; Pennington 1997; Welsh et al. 1991).

#### 4.2. Developmental disorders in children

A further source of evidence relevant to the developmental differentiation of fluid skills from g is provided by the study of cognitive impairment among individuals with specific developmental disorders. Studies examining a variety of developmental disorders of childhood indicate that children with attention deficit hyperactivity disorder (ADHD), early and continuously treated phenylketonuria (PKU), and specific learning disabilities (LDs) exhibit impaired performance on measures of EF but general intelligence in the normal range (Barkeley 1997; Berlin 2003; Diamond et al. 1997; McLean & Hitch 1999; Stanovich et al. 1997; Swanson 1999). Furthermore, some studies have identified specific patterns of fluid deficits associated with different disorders. In an examination of four developmental disorders, ADHD, autism, conduct disorder (CD), and Tourette syndrome (TS), consistent EF deficits were identified in ADHD and autism but not CD and TS. More severe deficits relative to IQ-matched controls were observed in autism compared with ADHD. In contrast, children with ADHD exhibited greater deficits in inhibitory processes relative to autism (Pennington & Ozonoff 1996).

Prima facie developmental evidence for the distinction between fluid cognitive functions and measures of g is provided by work on specific LDs, as defined in the United States. In LD as defined in the United States, deficits in fluid cognition impair learning and academic achievement, but general intelligence is in the normal range. Examination of EF in studies of both reading and math disability have indicated fluid cognitive impairments in comparisons with age-matched and, to some extent, ability-matched (i.e., younger) controls. Differences in the maintenance of information in working memory and in executive control, but also in speed of processing, have been noted in the presence of measured intelligence in the normal range (Bull & Scerif 2001; McLean & Hitch 1999; Pennington 1997; Sikora et al. 2002; Swanson & Sachse-Lee 2001; Willcutt et al. 2001).

Although fluid cognitive deficits are certainly not the only problem that children with LD as defined in the United States face, these problems can be substantial and would appear to contribute to the observed discrepancy between measured intelligence and academic achievement for these individuals. In reading disability, for example, difficulty with word identification has been related by using fMRI to decreased brain activation in two posterior left hemisphere systems associated with phonological processing (McCandliss & Noble 2003; Pugh et al. 2001). However, young impaired readers also exhibit lesser PFC activation on some phonological tasks than do non-impaired readers, suggesting some fluid cognitive involvement in reading impairment. Most interesting, older dyslexic readers demonstrate larger frontal activations in response to phonological tasks than do non-impaired readers (Shaywitz et al. 2002). Such a pattern of activation may suggest a compensatory effort whereby poor readers come to draw more heavily on fluid functions when engaged in a reading task.

Additionally, such increased activation may also indicate reduced processing efficiency in the PFC of impaired readers. Here, frontal activations in comparisons of non-impaired and dyslexic readers suggest that fluid cognitive deficits will impair reading progress both for non-impaired readers and for individuals with dyslexia and that the severity of reading difficulty will be greatest among individuals exhibiting fluid-function deficits in combination with posterior phonological processing-system deficits.

Given fluid cognitive deficits and the demonstrated interrelation of anterior and posterior brain function in the study of reading and reading disability, it is interesting to ask whether there might be a developmental relation between fluid cognitive deficits and intelligence in children with LD. Do problems with fluid cognition and with crystallized processes associated with phonological processing and word recognition lead developmentally to lower IQ for these children? In a particularly powerful design for examining this question, twin pairs in which one of the twins had a reading disability but the other did not were assessed using Wechsler full-scale IQ and measures of fluid cognition (Pennington 1997). Although IQ was in the normal range for all participants, twins with reading disability exhibited lower full-scale IQ than did unaffected co-twins, and both affected and unaffected twins exhibited lower full-scale IQ than did a matched control sample of twins in which neither twin had a reading disability. Furthermore, both affected and unaffected twins in the reading-disability twin pairs exhibited reduced EF in comparison with the matched control twin pairs. Overall, the control twins were found to have higher IQ and EF than both the typically developing twin and the reading disabled twin in a linear pattern of results that would seem to indicate that cognitive deficits associated with reading impairment lead to delayed development of general intelligence. However, the absence of IQ subscale information on performance and verbal IQ components of the Wechsler battery, which are generally associated with fluid and crystallized aspects of intelligence, respectively, limits inference. It may be that some proportion of the full-scale IQ difference both within and between the reading-impaired and non-impaired twin pairs is attributable specifically to reduced performance or verbal IQ.

### 4.3. Research on schizophrenia and phenylketonuria

Findings indicating a relative performance IQ or verbal IQ deficit in the measurement of intelligence in reading disability would be of some interest given evidence for fluid cognitive impairments and performance IQ deficits in the presence of full-scale IQ and verbal IQ in the normal range in schizophrenia (Egan et al. 2001). Although examinations of premorbid and postmorbid IQ among schizophrenics suggest full-scale IQ decline with disease onset, estimation of premorbid full-scale IQ has been based on postmorbid reading and language scores and, for this reason, inference regarding premorbid to postmorbid IQ change should be viewed with caution. The performance IQ subscales of the Wechsler battery have higher fluid cognitive demand than do the verbal intelligence scales, and patients with schizophrenia exhibit deficits in abstraction and attention greater than would be expected from postmorbid verbal and full-scale

IQ. In fact, performance IQ decrements appear in some instances to account for most, if not all, of the full-scale IQ discrepancy observed between patients and matched controls (Kremen et al. 2001). Estimation of premorbid full-scale IQ by relying on reading ability and academic achievement would therefore be invalid to the extent that premorbid performance IQ may have been significantly lower than premorbid verbal IQ. Evidence for just such a discrepancy is provided by two studies, one a prospective cohort study and the other a case-control design. Both indicate substantial increase in risk for schizophrenia associated with premorbid fluid-skills deficits and with significantly low premorbid performance IQ relative to verbal IQ in individuals developing the disorder (Aminger et al. 2000; Gunnell et al. 2002).

However, population-based cohort data from the Israeli Draft Board indicate that adolescents diagnosed as suffering from schizophrenia and adolescents identified as having schizotypal personality disorder (SPD) score lower than do healthy adolescents not only on fluid intelligence as measured by Raven's matrices test but also on measures of crystallized intelligence as assessed by the WAIS-R arithmetic subtest and by a modified Otis-type verbal intelligence test (Weiser et al. 2003). It is important to note that adolescents with schizophrenia and those with SPD in this population had significantly fewer years of education than did normal controls. Controls had on average 11.23 years of education (SD = 1.65) at the time of draft-board assessment while individuals with SPD had 9.06 (SD = 3.35) and those with schizophrenia 7.38 (SD = 3.74) years of education. The authors of this study elected not to control for years of education in analyses of differences in cognitive function between groups, citing Meehl's description of the matching fallacy that "disease in an individual both impedes education and impairs cognitive abilities measured in intelligence tests" (Weiser et al. 2003, p. 37). Although not controlling for years of education in this context is certainly a defensible choice in analysis, it is plausible that doing so would have indicated levels of crystallized ability appropriate for level of education in the SPD and schizophrenic groups but deficits in fluid function.

Further support for the idea that early fluid-skills deficits may be characteristic of risk for schizophrenia and responsible for observed low-normal full-scale IQ in individuals with schizophrenia is provided by examinations of neuropsychological profiles among adult patients, their unaffected siblings, and matched controls. These studies indicate that cognitive differences among the groups are primarily observed in tests of fluid skills. Comparison of patients with controls has indicated substantial deficits in neuropsychological tasks requiring abstraction and attention and has demonstrated that these deficits are most pronounced in patients with lower full-scale IQ (Kremen et al. 2001). Of further interest, studies of patients, siblings, and controls indicate that fluid-skills deficits relative to matched controls are present in the siblings of schizophrenic patients, suggesting an underlying fluid cognitive liability for the disorder (Egan et al. 2001). It is important to note, however, that measures of achievement and full-scale IQ as assessed by the WAIS discriminate patients from siblings and from matched controls, but do not discriminate patients' siblings from matched controls. In contrast, measures of fluid skills do tend to discriminate all

three groups, with discrimination between siblings and matched controls being largest for siblings of probands exhibiting impaired cognition on the particular measure being examined. As with the findings of Duncan et al. (1995) and Waltz et al. (1999) in the study of adults with lesions of the PFC, normal full-scale IQ as measured by the WAIS is observed in the presence of fluid-skills deficits in adults with schizophrenia and their unaffected siblings. These studies identify normal to low-normal crystallized IQ and achievement in schizophrenic patients and their siblings in the presence of deficits in types of fluid abilities that are highly correlated with general intelligence.

It is important to point out, however, that intelligence in schizophrenia has been of necessity studied almost exclusively with adult samples. Bedwell et al. (1999) provide perhaps the only developmental data on schizophrenia in childhood. Although their study sample is small, reflecting the rarity of childhood-onset schizophrenia, findings indicated a lack of raw-score change with age on the information subtest of the Wechsler Intelligence Scale for Children (WISC), an aspect of crystallized intelligence, in addition to deficits in subtests with a fluid component, namely, picture arrangement and block design. The lack of raw-score change indicates a failure to demonstrate developmentally normative increases in general knowledge and would seem to be at variance with the literature on intelligence in schizophrenia in adulthood, which suggests little crystallized deficit. Furthermore, the lack of raw-score change in the information subtest was correlated with post-schizophrenic hippocampal volume. Given findings discussed in section 5.2 indicating a strong relation between hippocampal volume and fluid cognition in schizophrenia (Weinberger et al. 1992), these data lend themselves to the interpretation that the fluid deficits of patients with childhood-onset schizophrenia impair the acquisition of new information and that this, in part, contributes to observed full-scale IQ declines. Such an association would be consistent with a developmental relation between fluid and crystallized intelligence, and perhaps the study by Bedwell et al. (1999) provides one source of data supporting this relation in childhood.

A second source of evidence regarding the developmental relation between fluid and crystallized ability is provided by the study of the cognitive development of children with phenylketonuria (PKU). Children with the inborn error of metabolism that limits the synthesis of phenylalanine (Phe) develop severe mental retardation if levels of Phe are not controlled through a strict dietary regimen. The buildup of Phe reflects the failure of the synthesis of Phe into Tyrosine (Tyr), a dopamine precursor. Given the predominant role of dopamine in the function of the prefrontal cortex (Sawaguchi & Goldman-Rakic 1991), also described in section 5.2 and the sections that follow, reduced levels of Tyr are associated with fluid cognitive impairments in children treated early and continuously for PKU (Diamond et al. 1997; Welsh et al. 1990). Specifically, although reduction of Phe prevents severe mental retardation, it results in lower levels of Tyr and reduced dopaminergic function in the PFC, leading to impaired ability on measures of fluid skills in children treated early and continuously for PKU (Diamond & Herzberg 1996; Diamond et al. 1997; Puglisi-Allegra et al. 2000).

Given the presence of fluid cognitive deficits in PKU, it is of some interest that individuals with PKU tend to

exhibit IQ and academic achievement in the low-normal range. Although it is not certain that fluid cognitive impairment is responsible for the low-normal full-scale IQ of children with PKU, this may be the case, as the cognitive abilities of children with PKU on a variety of other tasks associated with intelligence do not appear to be impaired (Diamond et al. 1997). In one of the few studies, if not the only one, to examine the performance versus verbal IQ distinction in children with PKU, a significant decrement in performance IQ relative to verbal IQ was observed at age eight years (Griffiths et al. 2000). Deficits relative to the population norm were observed in all performance IQ subtests, including the block design, object assembly, picture completion, picture arrangement, and coding subtests. Interestingly, a deficit was also noted in one verbal IQ subtest – the information subtest – but not in the similarities, arithmetic, vocabulary, and comprehension subtests. The pattern of results involving performance IQ deficits and a deficit in only the information subtest of the verbal IQ subscales is striking in its similarity to that of Bedwell et al. (1999) in the study of intelligence in childhood-onset schizophrenia and provides further evidence of specific dissociation of fluid and crystallized cognitive abilities early in the life span.

## 5. Developmental neuroscience of cognition and emotion

### 5.1. Neuroscience of developing fluid cognition

The evidence reviewed to this point offers little support for a close association between fluid cognition and general intelligence. Evidence for the unity of working memory and *g* notwithstanding, a number of studies suggest dissociation of fluid cognitive functions from *g*. On the one hand, it would seem without question that the ability to integrate diverse information in working memory is central to human reasoning and problem-solving ability and thereby to general intelligence (Duncan 2001; Miller & Cohen 2001; Prabhakaran et al. 2000). But given the discrepant evidence outlined in sections 3 and 4, what exactly is the relation between fluid functioning and general intelligence? If fluid cognitive functions are somehow less central to *g* than was once thought, then what do we know about the development of fluid cognition and how can this knowledge shed light on the idea that fluid functions can appear so central to intelligence in one instance and yet so distinct in another? Furthermore, what are the implications of dissociation of fluid cognition and *g* for understanding cognitive development and the assessment of human cognitive abilities and what is the state of measurement available for this assessment? These are central questions, relevant to both basic and applied science study of human cognitive function; relevant to basic science understanding of brain-behavior relations in the study of cognitive ability and relevant to applied science understanding of how to best measure and support mental development and the real-world functioning to which it is related.

Fortunately, neuroscientific study of fluid cognition offers some insight into why fluid functions are to some extent distinct from *g* and what this means for the relation of fluid cognition to real-world competence. Specifically, it is well established that areas of the PFC and ACC known

to be important for fluid cognitive functions and performance on tests of fluid intelligence (Braver et al. 1997; Duncan et al. 2000; Gray et al. 2003; Prabhakaran et al. 2000) are extensively and reciprocally interconnected with limbic and brain-stem structures associated with emotional reactivity, the stress response, and autonomic function (Allman et al. 2001; Bush et al. 2000; Diorio et al. 1993; Drevets & Raichle 1998; LeDoux 1989; Paus 2001; see the edited volume by Uylings et al. 2000). In combination, prefrontal, limbic, and brain-stem structures integrate cognitive, emotional, and autonomic responses to stimulation with the primary implication of such reciprocal innervation and regulation being that prefrontally mediated fluid cognitive processes directly influence *and, most important for present purposes, are influenced by emotional and autonomic responses to stimulation* (Erickson et al. 2003; de Kloet et al. 1999; Groenewegen & Uylings 2000; Kaufman & Charney 2001). A traditional view of reasoning ability as distinct from or liable only to disruption from emotional arousal has been replaced by a model in which cognitive, emotional, and autonomic responses work in concert to organize patterns of behavior (Davidson 2002; Van Eden & Buijs 2000).

### 5.2. A neural basis for cognition-emotion reciprocity in fluid cognition

The integration of cognitive, emotional, and autonomic responses to stimulation in the PFC is directly relevant to understanding fluid cognition and its distinction from psychometric *g*. What this integration means is that in order to understand fluid cognition it is important to understand that the prefrontal cortical structures and functions thought to closely reflect *g* are dependant to some extent on brain structures and functions that underlie emotional reactivity and the stress response. Brain structures that subserve working memory, attention shifting, and inhibitory control, all aspects of fluid cognition, and those that subserve emotional and stress reactivity are integrated in what is referred to as a *corticolimbic circuit*, that is, a circuit of reciprocal neural interconnectivity among dorsolateral, ventromedial, and orbitofrontal areas of the PFC, the ACC, and amygdaloid and hippocampal structures of the limbic system. The functioning of this neural interconnectivity in part underlies performance on fluid cognitive tasks such that dysfunction in one component of the system is likely to lead to difficulty in the self-regulation of cognition, emotion, and behavior (Davidson 2002; Posner & Rothbart 2000).

Brain-imaging studies of the processing of attention- and emotion-related information in the PFC and ACC indicate the integrated and reciprocal relation between affect and cognition in the brain. Distinct regions of the ACC are activated in response to cognitive tasks and to stimuli eliciting emotional arousal (Bush et al. 2000; Drevets & Raichle 1998). Similarly, examinations of intentional reappraisal of emotional arousal and of changes in emotional state associated with emotionally arousing stimuli have indicated reciprocal prefrontal cortical-limbic activation (Mayberg et al. 1999; Ochsner et al. 2002). With reappraisal of negative emotion and recovery from sadness and depression, prefrontal and cognitive ACC activation is increased and limbic and emotional ACC activation is decreased. During periods of negative

affect without reappraisal, however, limbic and emotional ACC activation is increased and prefrontal and cognitive ACC activation is decreased. Such reciprocal interconnectivity of emotion and cognition in the brain is highly consistent with the idea that fluid cognitive functioning is goal directed. Working memory and cognitive control processes are utilized in the service of specific goals related to problem solving and learning. However, at high levels of emotional arousal, fluid cognitive functions become inhibited, and impairments in the control of attention, working memory, and inhibitory control are more likely to occur.

In the study of emotion-cognition reciprocity in the brain, the amygdala has been shown to play a central role in threat detection and fear reactivity (LeDoux 1995; 1996), directing attention to ambiguity and enhancing vigilance in response to uncertainty (Whalen 1998). Such a role is in keeping with evidence that the amygdala directs cognitive and autonomic responses to sources of potential threat (Davidson 2002). Very high levels of threat or fear are thought to activate a relatively automatic link between the amygdala and the "fight/flight" response of the sympathetic branch of the autonomic nervous system that essentially bypasses or inhibits higher-order fluid cognitive appraisal and response processing of threat-related stimuli (LeDoux 1996). Such an automatic response to threat would confer a substantial evolutionary advantage and, as such, would tend to be highly conserved across species. Electrophysiological and brain-imaging evidence in human and nonhuman animal models attests to the reciprocal modulation of activity between the amygdala and the PFC in response to fear-evoking stimuli. Direct electrical recording of brain activity in rats through electrodes implanted in dorsolateral PFC and amygdala has demonstrated that decreased activity in the PFC in response to fear-evoking stimulation is attributable to increased amygdala activity (Garcia et al. 1999). Similarly, brain imaging in humans has demonstrated that perceptual processing of fear-evoking stimuli is associated with amygdala activation whereas cognitive evaluation of these stimuli is associated with increased PFC activation and decreased amygdala activation (Hariri et al. 2003).

Furthermore, amygdala activation plays an important role in the formation of highly stable long-term memories associated with stressful and highly emotionally arousing events (McGaugh et al. 1996; Roozendaal 2000). The mechanism through which the amygdala performs this function is modulation of stress hormones known to be important for memory storage. Such a system is highly adaptive in unpredictable environments, serving to promote survival by instantiating relatively automatic sympathetic responsiveness to indicators of impending threat or harm. However, in the instance of extreme trauma, the relative automaticity associated with this memory system, as an aspect of corticolimbic connectivity, appears to be highly detrimental to the effortful cognitive regulation of emotion, cognition, and behavior, as in the occurrence of post-traumatic stress disorder.

Effortful cognitive control by the PFC of negative emotion and stress reactivity associated with the amygdala would seem to be the norm rather than the exception and to occur through reciprocal connectivity of the ventromedial and orbitofrontal regions of the PFC, the hippocampus, and the amygdala (Davidson 2002; Davidson et al. 2000). Ventromedial PFC appears to be central in

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representing the emotional valence of stimuli, and its integrity is essential for holding in mind and acting on information of motivational significance to the organism. Disruption of the ventromedial PFC results in difficulty in the regulation of emotion and is associated with anomalous decision-making in response to information regarding the likely reward or penalty associated with a given choice (Bechara et al. 1996; 1999). In individuals sustaining damage to ventromedial PFC, negative consequences associated with aversive contingencies appear not to be marked with somatic or autonomic responses that serve to signal the individual not to engage in a particular behavior (Bechara 2004; Damasio 1994). The absence of an anticipatory autonomic response to perceived penalty and adverse decision-making associated with this absence have been observed in several studies (Bechara et al. 1996). As well, laterality in this system has been observed such that the right ventral medial PFC appears to play the central role within the corticolimbic system in reactions to stressful or aversive contingencies (Sullivan & Gratton 2002). Such laterality is consistent with the relative right-sided electroencephalographic PFC activation (left hypofrontality) observed in individuals with affective disorders (Davidson 2002; Sutton & Davidson 1997).

The hippocampus is understood to be integral to the information maintenance and cognitive control functions of the PFC through the rapid encoding of spatial and temporal context. Through relations with the amygdala and ventral and dorsolateral PFC, the hippocampus plays a pivotal role in cognition-emotion interaction. Studies of hippocampal function in rats and monkeys and in computational neural network models indicate that the hippocampus plays this role in part by modulating the action of dopamine in the PFC. Hippocampal damage in rats and monkeys has been shown to impair working memory functions by disrupting the responsiveness of PFC neurons to dopamine (Bertolino et al. 1997; 2002; Lipska et al. 2002a; 2002b). In contrast, increased hippocampal synaptogenesis in rats has been associated with increased spatial learning and memory (Lee & Kessner 2002; Liu et al. 2000). Similarly, hippocampal representation of context has been demonstrated using computational modeling to facilitate the maintenance of competing sets of representations and the emphasis of task-relevant and inhibition of task-irrelevant processes and information (Cohen & O'Reilly 1996). Disruption of hippocampally dependent representation of contextual information in a neural component corresponding to neuromodulatory effects of dopamine in the PFC has also been suggested to account for fluid cognitive deficits in schizophrenia (Cohen & Servan-Schreiber 1992). This computational model is consistent with the study of cognition in schizophrenic patients which indicates that cognitive function and cerebral blood flow in the dorsolateral PFC in response to the Wisconsin Card-Sorting Task (WCST), a well-known and widely used measure of fluid functioning, 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. Particularly impressive in this study is the finding that 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.

### 5.3. Fluid functioning and the integrity of corticolimbic connectivity

Although brief, the foregoing examination of some of the behavioral and psychological implications of prefrontal corticolimbic connectivity serves to emphasize that the fluid cognitive functions of the PFC are dependent, perhaps to a large extent, upon the integrity of this connectivity. Accordingly, a further point central to the overall thesis of this target article is that the integrity of the corticolimbic system that underlies fluid cognition depends upon the activity of the hypothalamic-pituitary-adrenal (HPA) axis, the physiological stress-response system. As detailed in many comprehensive reviews, the HPA axis regulates the glucocorticoid hormone response to stress and does so through positive-feedback and negative-feedback mechanisms involving the amygdala, hippocampus, and PFC (Kaufman & Charney 2001; Lopez et al. 1999; Vazquez 1998). In the stress response, levels of circulating glucocorticoids are controlled by the activity of the paraventricular nucleus of the hypothalamus through cascading effects on the pituitary and adrenal glands. Glucocorticoids stimulate activity of the central nucleus of the amygdala and work to maintain a state of arousal in response to threat. The PFC and the hippocampus, in turn, respond to glucocorticoid increase with negative feedback on the central nucleus of the amygdala and structures involved in glucocorticoid response to stress to down-regulate levels of glucocorticoids (Francis et al. 1999a).

A notable consequence of the bidirectionality of the HPA system is that high levels of stress early in life influence its development. The homeostatic balance of the system in its ability to regulate the neuroendocrine response to stress appears to be established early on. The primary mechanism of this early experience effect as demonstrated in rodents involves tactile stimulation associated with maternal care (Caldji et al. 2000a; 2000b; Francis et al. 1999b). In rats, high levels of maternal licking and grooming of pups and the occurrence of a nursing style known as *arched-back nursing* are associated with high levels of cognitive and behavioral competence. The effect of this maternal rearing style has been shown to be associated with increased synaptogenesis in the hippocampus, increased benzodiazepine and gamma-amino-butyric acid receptor binding within structures of the corticolimbic circuit including the PFC that allows for increased down-regulation of circulating glucocorticoids, and enhanced cognitive function as assessed by learning and spatial memory tasks (Francis et al. 1999a; Liu et al. 2000). However, high levels of stress early in life that result from prenatal or postnatal stress and/or disruptions to maternal care are associated with the opposite of this pattern. Rats experiencing stress prenatally or extended maternal separation in the neonatal period exhibit reduced ability to regulate the activity of the HPA axis, higher levels of circulating glucocorticoids, and reduced hippocampal synaptogenesis (Gould & Tanapat 1999; Liu et al. 2000).

One consequence of this poor regulation of HPA activity and reduced hippocampal synaptogenesis is

disrupted dopaminergic innervation of the PFC. In rats experiencing extended maternal separation and social deprivation as neonates, several regions of the PFC exhibited reduced dopaminergic innervation by age 45 days (Braun et al. 1999). As noted in section 4.3, there is clear evidence that dopamine plays a prominent role in regulating the fluid cognitive functions of the PFC (Brozoski et al. 1979; Diamond et al. 1997; Goldman-Rakic 1999; Lewis et al. 1999). Computational, lesion, and transient inactivation models provide considerable evidence of disrupted dopaminergic activity in the PFC and impaired functioning of prefrontal neurons associated with early hippocampal pathology and high levels of circulating glucocorticoids (Bertolino et al. 1997; 2002; Kinnunen et al. 2003; Lindley et al. 2002; Lipska & Weinberger 2000a; Meyer-Lindenberg et al. 2002; Saunders et al. 1998; Seamans et al. 1998; Weinberger et al. 2001). That the effect appears to be a developmental one is indicated by the demonstration that neonatal but not adult lesions of the ventral hippocampus in rats and monkeys are associated with impaired performance on a variety of working memory and learning tasks dependent upon dopamine function in the PFC (Chambers et al. 1996; Le Pen et al. 2000; Lipska et al. 2002).

The foregoing suggests that fluid-skills deficits are likely to be associated with adverse rearing conditions and may be partially mediated through stress-related disruptions of hippocampally modulated dopaminergic innervation of the PFC and stress-related disruption of the responsiveness of prefrontal cortical neurons to multiple neurotransmitter systems. Given the principle of use-dependent synaptic plasticity and the fact that the PFC is relatively slow in maturing (Gogtay et al. 2004), it may be that patterns of limbic-prefrontal reciprocity become biased toward either emotional-reactive or cognitive-regulatory types of responding fairly early in life. High levels of stress or threat might lead to patterns of primarily autonomic reactive responses to stimulation rather than effortful fluid cognitive responses. Lifelong patterns of reciprocity are almost certainly not established by early experience, but, in young children, the development of fluid cognition and the many aspects of behavior to which fluid cognition is related, may be driven to some extent by early experience and its effect on emotional reactivity and regulation. Individuals with a lower threshold for emotional reactivity and stress responding associated with the amygdala and related limbic structures may experience difficulty with fluid cognitive functioning, particularly when reared in high-stress environments.

However, the extent of stress required to bring about fluid cognitive deficits and the applicability of animal models to human populations are open to question. As well, the exact mechanisms through which dopamine and other neurotransmitter functions in the PFC are disrupted by early hippocampal pathology remain uncertain (Lipska & Weinberger 2000a; Lipska et al. 2002). Interactions of dopamine with glutamatergic and GABAergic systems in the PFC indicate both inhibitory and excitatory roles for dopamine (Lewis et al. 1999; Yang et al. 1999), suggesting that dopaminergic tuning of prefrontal pyramidal neurons may underlie both inhibitory control and information maintenance functions of working memory (Braver et al. 1999; Cohen & Servan-Schreiber 1992; Miller & Cohen 2001). However, the specific role of

dopamine in the prefrontal cortex is complex and elucidation of its specific and selective effects remains a work in progress (Durstewitz & Seamans 2002).

## 6. Implications of developing corticolimbic circuitry for intelligence in human populations

### 6.1. Stress and early experience

Neurobiological evidence relating corticolimbic connectivity to fluid cognitive skills and demonstrations of the effects of stress-related HPA activity on the integrity of this circuit suggest plausible mechanisms through which early chronic rearing stress affects the development of one aspect of what has generally been regarded as intelligence in human populations. In the neuroscience literature, neonatal hippocampal damage has been referred to as an animal model of schizophrenia (Lipska & Weinberger 2000b). This is largely due to the fact that some of the effects of neonatal hippocampal manipulations on specific schizophrenic-like phenotypic traits emerge after the pubertal period in affected rats. Effects of hippocampal disruption on aspects of learning and working memory, however, appear prior to puberty (Chambers et al. 1996), in itself a phenotypic trait consistent with early risk for schizophrenia in human populations (Ammeringer et al. 2000; Gunnell et al. 2002). In particular, as already noted, neonatal but not adult lesion of the hippocampal formation is associated with working memory deficits both prior to puberty and in adulthood in rodents and nonhuman primates. In contrast, working memory deficits associated with PFC lesions are seen only when the lesions are made in adulthood and not in the neonatal period (Bachevalier et al. 1999; Lipska et al. 2002; Malkova et al. 2000; Weinberger et al. 2001).

Of similar interest regarding fluid cognitive deficits as seen in PKU is evidence indicating that high concentrations of phenylalanine attenuate synaptic plasticity in the rat hippocampus (Glushakov et al. 2002). As synaptic plasticity in the hippocampus is known to be associated with aspects of fluid cognition (Liu et al. 2000), these results suggest fluid cognitive impairment associated with PKU results from disruption to the integrity of the corticolimbic circuit similar to that observed in schizophrenia and in animal models of the effect of stress on developing fluid cognitive skills. However, it is important to note that moderate concentrations of Phe, such as those observed by Diamond et al. (1997) in individuals treated early and continuously for PKU, may have lesser effects on synaptic plasticity. It may be that the effect of moderate levels of Phe on hippocampal synaptogenesis combined with reduced levels of Tyr is sufficient to produce the reduced dopaminergic function and working memory deficits in individuals with early and continuously treated PKU (Diamond & Herzberg 1996; Diamond et al. 1997), but such a mechanism remains to be determined.

In light of research on fluid cognition in schizophrenia and PKU, evidence relating rearing stress to reduced hippocampal synaptogenesis and to working memory deficits in nonhuman animal models provides perhaps one plausible neurobiological model for the effects of environmental disadvantage and disrupted early rearing experience on the development of one aspect of intelligence in humans. Nonhuman animal models of the development of working

memory indicate that chronic early rearing stress affects the activity of the HPA axis with attendant negative consequences for hippocampal function and aspects of fluid cognition dependent upon the corticolimbic circuitry of the PFC. As a result, early life stress would be expected to attenuate fluid cognitive functions in human populations in ways that might appear to underlie deficits in general intelligence. Given a large number of studies demonstrating moderate to high heritability for general intelligence but also considerable environmental influence on intelligence, particularly early in the life span (Gottlieb et al. 1998; Wahlsten 1997), developmental neuroscience work on the role of chronic stress in the development of corticolimbic connectivity and the integrity of the PFC provides evidence of a putative mechanism through which early rearing stress, and conversely early education and care intervention, would appear to influence one prominent aspect of developing cognition in humans.

Such a relation among early stress, enriched early experience, and later developmental competence has been demonstrated in rats. Specifically, Francis et al. (2002) and Bredy et al. (2003) demonstrate reversal of the effect of chronic early stress on later stress responsivity and behavior among rats receiving environmental enrichment during the post-weaning period. As with prior studies, these studies suggest a functional reversal of the effects of life stress by compensatory mechanisms that alter the phenotypic expression of the underlying stress reactivity associated with antenatal or early postnatal stress (Maccari et al. 1995; Whimbey & Dennenberg 1967). In humans, it is well known that inconsistent or inadequate caregiving and disruption to the early rearing environment are aspects of risk for poor developmental outcomes in children growing up in low socioeconomic status (SES) environments (McLoyd 1998). As is also well known, early compensatory caregiving interventions such as the Abecedarian Project (Ramey & Campbell 1991; Ramey et al. 1998) have demonstrated effects on IQ and on multiple aspects of developmental competence from birth through adulthood in randomized designs involving children at high risk for low IQ as a result of low SES. Presumably one of the mechanisms through which compensatory education and care among humans leads to enhanced competence is through the attenuation of early stress and adverse neurobiological consequences associated with chronic rearing stress. Therefore, one important future direction for work on early intervention will be the identification of specific stress mechanisms and demonstrations of the ways in which early intervention reduces rearing stress and affects neurobiological development and cognitive functioning.

### **6.2. Stress, early intervention, and intelligence in human populations**

Work in developmental neuroscience indicates that chronic early rearing stress can lead to disruptions in essential neural systems underlying fluid cognitive skills with nonhuman animal models providing evidence that developing corticolimbic connectivity underlies the integrity of functioning of the PFC. But could environmental influences on developing corticolimbic connectivity really underlie the development of general intelligence? Even though evidence for disrupted fluid skills associated

with the effects of early chronic stress on developing corticolimbic connectivity in nonhuman animal models may be compelling, the relation of developing fluid functions to the development of intelligence and to estimates of general intelligence in human populations remains unclear. Would general intelligence really be affected by high levels of rearing stress and/or by programs designed to eliminate that stress? Jensen (1998) examines the early intervention literature and declares that no study, with the possible exception of the Abecedarian Project, actually changed *g*. However, given the previously established relation of fluid skills to *g* (Gustafsson 1988), it would be expected that programs that could promote fluid-skills functioning through the enhancement of corticolimbic connectivity would at least appear to influence general intelligence. Certainly findings from imaging studies and single-cell-recording studies indicate a highly flexible and adaptive role for the PFC in coordinating diverse information streams and attest to the centrality of fluid skills in any conceptualization of intelligence (Duncan 2001). However, given the aforementioned evidence suggesting dissociation of fluid cognitive functions from intelligence as measured by standard assessments, it may be the case that early environment affects specific aspects of cognition – namely, fluid functions – that closely resemble but are distinct from psychometrically defined general intelligence. Of course, whether such a mechanism related to fluid cognition is actually present in early intervention for children in poverty and whether such a mechanism would be associated with enhanced corticolimbic functioning and lead to the appearance of increased general intelligence are open questions. In investigating such questions, however, it is necessary to keep in mind that the effects of poverty and, conversely, environmental enrichment on child development are quite diverse and perhaps have as much or more to do with the promotion of crystallized knowledge or the diminution of the adverse effects of poor nutrition and inadequate health care on child outcomes as with anything associated with stress and fluid cognition.

### **6.3. Genetic and environmental influences on developing cognitive abilities**

Although the study of early intervention for children facing psychosocial disadvantage may shed potentially valuable light on relations between stress and cognitive development, another approach to questions about environmental influences on fluid cognition and their relation to general intelligence is found in behavior genetics research. For some time now, it has been well established within the framework of behavior genetic twin and adoption study designs that both genetic and environmental influences act on general intelligence and that some substantial proportion of variance in general intelligence is accounted for by genetic variation. If fluid cognition is similar to but distinct from general intelligence and more liable to environmental influence, it should be possible to demonstrate this by using the variance-partitioning methods of behavior genetics research. Indeed, although behavior genetic examinations of working memory and general cognitive ability are somewhat rare, those that do exist indicate that working memory is distinguishable from general intelligence both genetically and environmentally.

Specifically, for the working memory measures that have been examined, common genetic variance is not particularly large, and both genetic and nonshared environmental loadings on the measures are distinct from those associated with general intelligence (Ando et al. 2001; Luciano et al. 2001). However, these studies are limited by relatively low phenotypic correlation between working memory and general intelligence and have been conducted only with adult samples.

Although in need of replication, both with adults and children, findings indicating moderate to small common genetic variance in working memory are perhaps consistent with heritability estimates for *g* in childhood. Specifically, heritability estimates of *g* in young children are small, at about 20%, but increase to about 60% in adult samples (Plomin & Spinath 2002). Always something of a puzzle as to why heritability would increase with age, if environmental influences on fluid function are relatively large, and if fluid function is particularly relevant to IQ test performance in early childhood, then the noted change in heritability with age may be more apparent than real. Furthermore, if fluid function in the guise of the general factor is highly liable to environmental influence early in the life span, then heritability estimates of IQ would also be smaller for children from lower SES backgrounds. This is in fact the case, as estimates of environmental influence on measures of cognitive functioning in children increase and estimates of heritability decrease as a function of SES (Rowe et al. 1999; Turkheimer et al. 2003). Of particular note, in early childhood this modification of the heritability of IQ has been observed at age seven years on measures of full-scale and performance IQ but not verbal IQ as assessed by the Wechsler Intelligence Scale for Children (WISC) (Turkheimer et al. 2003). In an adolescent sample, however, modification of the heritability of IQ by SES was observed for a version of the Peabody Picture Vocabulary Test, a measure of crystallized knowledge (Rowe et al. 1999).

## 7. Measurement

### 7.1. Limits to the measurement of a single factor of intelligence

Although the available evidence does not as yet render a definitive conclusion regarding dissociation of fluid cognitive function and *g*, the psychometric, developmental, clinical, and behavior genetic data outlined in this target article do suggest a distinction between fluid cognitive function as examined in the cognitive and neuropsychological literatures and general intelligence as defined by researchers working within the psychometric tradition. This is very interesting because, as noted at the outset of this review, psychometric examinations of typically developing populations have found measures of fluid function to be essentially identical to general intelligence. Based upon evidence presented in this review, however, it would seem reasonable to conclude that fluid function is to some extent an indicator of the integrity of a corticolimbic brain system that reflects the interdependence of cognition and emotion in a way that renders it amenable to the influence of early environment and distinct from psychometric *g*. Differentiation of fluid cognition from general intelligence

would appear to be an important measurement goal for research on cognitive development.

Evidence for a distinct developmental trajectory for fluid cognition in the study of human cognitive abilities that is particularly rapid in early childhood calls into question the specific utility of measures of general intelligence, particularly for young children. The explicit measurement of a single factor may in many instances not be particularly informative regarding individual cognitive growth and the relation of that growth to adaptive functioning. Unfortunately, several widely used measures of mental abilities, including those frequently used with young children, excel as measures of general intelligence but are weaker as measures of specific cognitive ability factors (Caruso 2001; Laurent et al. 1992; Woodcock 1990). Perhaps of most immediate concern, as already noted, widely used measures of intelligence disproportionately assess crystallized skills and domains of intelligence associated with opportunity for learning (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 – crystallized skills broadly defined. Only approximately 7% of subtests directly assess fluid skills and perhaps another 10% assess processes and memory skills that have a fluid-intelligence component. Furthermore, nearly all of the fluid subtests were found on the WJ-R, the only measure explicitly grounded in *gF-gC* theory. The Wechsler batteries contain no explicit measure of fluid skills, and the Stanford-Binet IV was found to contain only one explicit measure of fluid skills. As noted by McGrew (1997), the underrepresentation of measures of fluid skills in widely used assessments of intelligence is considerable.

Given that many commonly used measures of IQ disproportionately assess crystallized mental abilities, intelligence as tested by these measures must be seen to be limited in specific ways. However, it may be that for typically developing children in typical environments, discrepancies between fluid and crystallized aspects of cognition are small or perhaps not particularly meaningful. This could be due to the fact that nurturing, low-stress environments also tend to provide high levels of educational stimulation. However, for children from chaotic or dysfunctional homes or otherwise facing some experiential or developmental disadvantage, the poor representation of fluid cognitive assessment on currently available measures of intelligence is perhaps particularly disadvantageous. As measures of crystallized skills, currently available assessment batteries will provide a limited perspective on the cognitive abilities of children. Furthermore, as has been already outlined in detail, chaotic rearing environments are likely to have distinct adverse effects on fluid aspects of cognition. Currently available measures, however, will not really be able to address these effects. From a single-factor perspective on the measurement of intelligence, the underrepresentation of fluid skills on most measures of intelligence would be of minimal concern. However, such an approach to measurement would not appear to be justified, as evidence from

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a number of sources indicates that increased precision in the assessment of developing fluid cognition in young children is needed.

### **7.2. Measuring fluid cognition**

Given the presence of fluid-skills deficits in a wide variety of developmental and learning disorders, increased attention to the measurement of fluid cognitive functions, referred to primarily as executive function in the study of young children, and their relation to widely used measures of intelligence and achievement is a high priority. It may be that identification of fluid cognitive deficits in the presence of typically developing crystallized abilities could prove to be an indicator of increased risk for developing psychopathology or learning disorder. Several cross-sectional studies examining normative developmental changes in aspects of EF provide an increasing knowledge base on fluid cognition in children. Findings indicate a general age-related progression on various EF tasks and differences among tasks in the age at which adult-level performance is reached (Krikorian & Bartok 1998; Luciana & Nelson 1998; Pennington 1997; Welsh et al. 1991). These studies have also demonstrated distinct information maintenance and cognitive control factors underlying EF task batteries (e.g., Pennington 1997). What is needed, however, is research within an individual-differences perspective relating differential performance at specific ages and developmental time periods to various outcomes and competencies. Although further work on normative levels of performance on EF tasks is needed, an equal priority is the need for cross-sectional and longitudinal research examining correlates of individual differences in task performance in both typically and atypically developing populations of children.

The need for the differentiation of fluid skills from  $g$  early in the life span would also seem pressing given evidence for the relation of fluid cognitive skills to academic achievement and to social competence in typically developing young children. Studies of achievement and behavior indicate broad influence of fluid cognitive functions on achievement in both reading and math and in social and emotional competencies known to be important for the adjustment to school (see Blair 2002 for a review). Examination of the relation of WJ-R measures of cognitive ability to WJ-R measures of academic achievement indicates distinct developmental relations of fluid and crystallized intelligence to progress in both reading and math. As expected, fluid skills show a predominant influence on achievement in early and middle childhood that declines by adolescence. In contrast, the relation between crystallized intelligence and reading and math achievement rises rapidly in late childhood and adolescence and remains very high in adulthood (Evans et al. 2001; McGrew & Hessler 1995). Furthermore, a relevant example for achievement in math concerns brain-imaging findings indicating bilateral PFC activation occurring during reasoning on math problems. While simple calculation processes have been associated with parietal and parieto-occipital regional activation, problems requiring multiple operations, that is, multiple calculations with intermediate steps, demonstrate PFC activation (Burbaud et al. 1995; Prabhakaran et al. 2001). Such prefrontal activation in response to multiple-operation problems

is consistent with imaging findings observed by Waltz et al. (1999) in the examination of brain activation occurring in response to increased relational complexity in problems adapted from Raven's Progressive Matrices Test.

Whether through facilitation of the acquisition of crystallized skills or as a separate influence on academic achievement in specific subject areas during early and middle childhood, fluid functions play a clear role in academic achievement early in the life course. Continuing attention to influences on and the measurement of fluid aspects of cognitive function in young children should prove particularly valuable for educational and social policy decision making. Perspectives on the development of intelligence and its relation to academic achievement that rely on the measurement of a single factor may be particularly disadvantageous. If children are having difficulty in learning, measures that conflate fluid and crystallized functions cannot differentiate whether children have limited opportunity to acquire the types of knowledge assessed by measures of crystallized intelligence or difficulty with the fluid skills associated with learning unfamiliar material, or both. There is an increasing emphasis on accountability in education; on the need to ensure that children acquire the crystallized skills that schooling can provide. In contrast, the development and application of knowledge about fluid skills and their perhaps unique role in early learning and development are currently inadequate. Particularly in the evaluation of the efficacy and effectiveness of preschool and early school readiness initiatives such as Head Start, emphasis on children's acquisition of crystallized skills such as those associated with early reading would be well served by an equal and complementary emphasis on the development of fluid cognitive abilities.

### **7.3. Differentiating fluid cognition from general intelligence**

If available evidence indicates the need to differentiate fluid cognition from general intelligence, an important next step is to ask how separable the constructs may be in typically developing populations. Here, the lead of Gustafsson (1988) may prove useful in a somewhat unexpected way. Specifically, having examined a number of hierarchical factor models of cognitive abilities, Gustafsson (1988) determined that the relation between  $gF$  and  $g$  was so strong as to indicate unity. Having arrived at this conclusion, he then made the insightful suggestion that it would be desirable to set  $gF$  identical to  $g$  and to purge the remaining second-order factors of their  $g$  variance. Doing so would enable one to study aspects of cognition on their own, independent of variation in them attributable to  $g$ . Purging  $gC$  of its  $g$  variance would result in a  $gC$  residual,  $gC'$ , that would represent crystallized intelligence independent of  $g$ . Similarly, with the other second-order factors,  $g$  variance could be removed, and differences among individuals in the residual variance examined.

Following Gustafsson's logic, evidence presented in this target article would suggest that there must also exist some  $gF$  residual,  $gF'$ , that can be purged of  $g$  variance and studied independently of  $g$ . The near unity of the relation between  $gF$  and  $g$  in the psychometric study of intelligence would seem to render this problematic; however,

in light of the evidence presented in this article, it would seem that measures of working memory and EF have important sources of variance independent of  $g$ . The need for such measurement would seem to be indicated and be in keeping with Carroll's (1996) call for increased experimental work examining the identity of  $gF$  relative to  $g$ . While acknowledging that Gustafsson (1988) may be correct in setting  $gF$  equal to  $g$ , Carroll speculated that "it is possible that measures of  $gF$  feature attributes that require specific skills in inductive and deductive reasoning that are not necessarily present in other measures of  $g$ " (Carroll 1996, p. 15).

Considering the possibility of removing  $g$  variance from  $gF$  raises the interesting question of whether the resulting indicator would in fact continue to resemble  $g$  in certain respects. Would  $gF'$ , defined as fluid cognition independent of  $g$ , function as something like a pseudo- $g$ , accounting for variance in a number of aspects of human functioning much like psychometrically defined general intelligence? That is, could some of the predictive power of the real  $g$  be due to its close association with fluid function? One source of evidence to examine this possibility might be analysis of patterns of test-score gains between cohorts on measures of intelligence to see whether variation in increases in crystallized scores could be accounted for by non- $g$  fluid cognitive gains. It may be that gains on crystallized aspects of cognition are attributable to non- $g$ -related gains in fluid function. Alternatively, it may be that all cognitive gains are highly compartmentalized and related to changes in specific aspects of experience. Evidence supporting this latter possibility is provided by studies that offer intensive training on fluid skills. Preliminary findings from two short-term but intensive working memory training studies with young children indicate that the training is associated with fluid cognitive gains as measured by Raven's matrices test (Klingberg et al. 2002) and the matrices section of the Kaufman Brief Intelligence Test (Posner & Rothbart 2004) but not on other aspects of cognition.

An additional or alternative explanation for any relation of non- $g$  fluid gains to gains in other aspects of intelligence, should they exist, however, would be that they represent processes related to motivation. Improvements in test scores associated with fluid skills could be indicative of enhanced motivation and engagement in testing situations. The role of motivational factors in cognitive test performance has been acknowledged for some time, particularly with children from low-income backgrounds and children and adults with IQ in the range of mental retardation (Zigler 1999; Zigler et al. 1973). Given evidence outlined early in this review indicating reciprocal relations among prefrontally based fluid cognitive functions and stress and emotion-related processes of the limbic system, it would not be surprising if positive relations between fluid cognition and performance on a variety of cognitive measures were mediated through greater engagement and reduced anxiety in testing situations.

Fluid cognition independent of  $g$  may be wide ranging in its influence. It may, for example, be relevant to the concept of successful intelligence as defined by Sternberg (1996). Successful intelligence refers to an individual's adaptability and persistence in response to new environments in ways that enable or promote the individual's

propensity to demonstrate competence – sometimes very high levels of competence. Measurement of  $gF'$  in the study of successful intelligence could prove informative, as the construct of successful intelligence has face validity but its relation to psychometrically defined intelligence is perhaps unclear. Support for the role of  $gF'$  in the study of human cognitive abilities could also add further empirical weight to Jensen's caution to readers of his 1998 book that  $g$  should not be seen as an all-encompassing variable; that it is only one among many factors that contribute to what passes for success in life. Evidence reviewed here indicates that  $gF'$  may very well be one of these other factors – one that is important to differentiate from  $g$ .

Of course, further work on measurement is needed in the delineation of fluid cognition from  $g$ . Studies measuring IQ in the presence of fluid-skills deficits have approached the problem from either a neuropsychological or psychometric framework, and rarely are the two combined to examine possible dissociations between the two types of measures. Further work using diverse measures with both typically developing and atypically developing populations could help to develop the measurement of  $gF'$ . This would be particularly valuable in the study of children for whom diverse aspects of cognition are developing rapidly. For instance, studies employing Raven's matrices test, an age-appropriate Wechsler battery, and a number of EF tasks might provide useful descriptive data on variations in performance. Such an approach would likely be of considerable diagnostic utility in addressing learning and/or behavior problems in children. A theoretically sound multi-measure assessment of this type is referred to as a *cross-battery approach* in the psychometric literature. Here, intelligence researchers, recognizing limits to the diagnostic utility of the general factor and of specific IQ measures, advocate for the use of subtests from diverse measures to explicitly examine variation in patterns of cognitive performance (Flanagan et al. 2000; McGrew 1997). Such a cross-battery approach to the differentiation of fluid functions from general intelligence and other second-order factors such as speed of processing would be valuable in the study of developmental disabilities and for designing innovative curricula and teaching approaches to meet the needs of diverse groups of children. It might also prove valuable in mental retardation research in further refining and defining the adaptive behavior construct. Here, fluid cognitive performance higher or lower than expected from estimates of  $g$  derived from a Wechsler battery would be expected to be a robust indicator of adaptive functioning.

Multi-measure studies could perhaps reveal something fundamental about fluid-cognition development and its relation to intelligence and behavior. One of the important points of such an approach is that expectations regarding dissociation among different cognitive measures be theoretically grounded and clearly specified a priori. The evidence reviewed in this article provides some conceptual and empirical basis for expected dissociation among aspects of intelligence. However, this does not by any means imply that fluid functions or other second-order factors typically lack  $g$  variance. On the contrary, the psychometric data clearly indicate that, in typical brains in typical environments, fluid functions may tend to go hand in glove with crystallized and other aspects of intelligence. However, in atypical brains in typical environments

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or typical brains in atypical environments, dissociation is not only possible but also perhaps likely.

## 8. Summary and conclusion

### 8.1. Fluid cognition as an independent construct

This review has presented evidence indicating fluid cognition to be a distinct neurobiologically grounded aspect of cognitive function, amenable to the effects of experience both cumulatively in terms of life stress/life opportunity and situationally in terms of the reciprocity between emotion and fluid cognition. Furthermore, the review has suggested that environmental stressors acting on PFC and limbic brain structures and functions may contribute to individual differences in fluid cognition and account to some extent for long-standing associations among low general intelligence, psychosocial and socioeconomic adversity, and risk for developmental disorder and psychopathology. As a corollary of this suggestion, the observation has also been made that the enhancement of fluid cognition may be an important aspect of compensatory education programs for young children facing early adversity and that the promotion of fluid cognitive ability through the disruption of stress-related processes by early intervention may prove to be one mechanism through which intervention effects occur. Accordingly, it is recommended that an increased emphasis be placed on normative and individual-differences research in the development of fluid cognition in young children, and the idea is proposed that fluid cognitive ability might account for some of the broad explanatory power of general intelligence. In particular, one of the seemingly unshakeable but continually disputed aspects of research on general intelligence has been the breadth of the construct's reach – the extent to which it has been shown to account for variation in so many aspects of human functioning. However, given evidence for an independent fluid-function construct outlined in this target article, it may be that some of this breadth can be accounted for by fluid cognitive skills. Specifically, the magnitude of positive correlations between measures of human cognitive abilities and life outcomes increases in proportion to the cognitive measures' loadings on  $g$ . For example, cognitive ability measures with high  $g$  loadings, such as measures of fluid skills, have higher correlations than do low  $g$  measures with column vectors extracted from scores measuring such things as performance on learning tasks, performance on elementary cognitive tasks, and nerve conduction velocity – all robust indicators of  $g$  (Jensen 1998). However, it may be that some of the relation between cognitive measures with high  $g$  loadings and life outcomes, particularly indicators of learning, job success, and other aspects of real world competence, is attributable to  $gF'$  as much as to  $g$ . If  $gF'$  were somehow partialled from these analyses, as it is not really  $g$ , some of the evidence supporting the broad explanatory power of  $g$  for life outcomes might be reduced, perhaps substantially.

By focusing on fluid cognition in thinking beyond the general factor, one might also question noted racial differences in general intelligence. Differences in mental abilities between blacks and whites increase with the size of the  $g$  loadings of various tests, being smaller on measures

of crystallized intelligence but more substantial on measures with high  $g$  loadings such as fluid skills. Here, at the population level, one might ask whether black-white differences have more to do with fluid cognition independent of  $g$  than with  $g$  itself and whether evidence regarding the  $gF'$  construct might to some extent support the idea that black-white intelligence differences have more to do with differences in the typical environments in which blacks and whites function in American society than with anything else. As already noted, fluid skills independent of  $g$  are liable to environmental influence in a number of ways. Identification of  $gF'$  might suggest that the intelligence of black Americans as well as ethnic groups the world over living in circumstances either less advantaged than or simply substantially different from that of the average white American, differs not so much as a function of  $g$  loadings of given cognitive measures as with a culturally loaded  $g$ , in which measures purported to be the best measures of general intelligence are those on which some groups may be least likely to do well. Certainly the idea that the intelligence deck is culturally stacked against some groups is not a new one. However, understanding the relation of fluid cognition and brain function to intelligence and to intelligence-test performance helps to illuminate cross-cultural differences in performance with an alternative, neurobiologically based experiential rather than narrowly defined hereditary explanation for that difference.

Furthermore, cultural loading not only in what is being tested, but in the testing process itself, could be informed by the  $gF'$  construct. It is well known that scores from specific cognitive test batteries should not be used to evaluate cognitive ability for individuals whose cultural and experiential background differs substantially from that of normative samples (Flanagan et al. 2000; Greenfield 1997). A more theoretically defensible assessment strategy for cross-cultural comparison, and one in keeping with the relation between fluid cognition and human behavior outlined in this target article, is a dynamic testing approach. In the dynamic approach, the emphasis is on the measurement of learning and test-score change during the assessment process, reflecting the ability of the examinee to incorporate feedback when attempting to complete a given cognitive task successfully. Empirical examination of such an assessment approach has indicated that scores obtained through a dynamic testing procedure are better indicators of school achievement in a rural African sample than are scores obtained from static testing procedures and that measures of fluid cognitive functions correlate positively with test-score increases in response to dynamic testing (Sternberg et al. 2002).

Although more work is needed, if ongoing investigation of  $gF'$  were to provide support for the construct, it is likely that many individuals invested in the study of  $g$  would welcome the opportunity to remove extraneous variance from its measurement and definition. It is, after all, the goal of factor analysis to get to the distillate of the various measures, factoring out aspects of cognition that are unrelated to  $g$  itself. However, proponents of the  $g$ -based understanding of human development and behavior (also described through clever word play as the “ $g$ -ocentric worldview”), in which general intelligence possesses enormous explanatory power, would likely protest, some vehemently. Some of the explanatory

power of  $g$  would likely be attributable to  $gF'$ . However, while such an end point would perhaps seem a blow to proponents of psychometric  $g$ , it would really represent a considerable advance for cognitive psychology and developmental neuroscience. Studies demonstrating influences on fluid cognitive functioning that are distinct from  $g$  provide an important source of information for the study of relations between mental ability and behavior. In particular, developmental neuroscience work on fluid cognition provides a valid neural architecture for clearly defined cognitive functions and processes that would seem to have brought the study of intelligence very, very close to a neurobiologically grounded explanation for individual differences in  $g$ . Such a unification of psychometric, componential, and neuroscientific approaches to the study of intelligence has for long been desired, and research relating prefrontal corticolimbic circuitry to working memory and to psychometric  $g$  would seem to have come as close as possible to filling the bill for the identification of a neural basis for general intelligence (e.g., Duncan et al. 2000). In fact, were it not for the dissociation data outlined in this target article, one might really craft a compelling story regarding individual differences in the neurobiology of the prefrontal cortex and general intelligence. However, it would seem that such an explanation would really amount to nothing more than a crafty story and that  $g$  remains as inscrutable as ever.

## Open Peer Commentary

### What we need is better theory, not more data

Mike Anderson

*School of Psychology, The University of Western Australia, Crawley, Western Australia, 6009, Australia*

[mike@psy.uwa.edu.au](mailto:mike@psy.uwa.edu.au)

<http://www.psy.uwa.edu.au/user/mike/biglab/biglab.htm>

**Abstract:** Although I find Blair's case for arguing for the distinction between fluid cognitive functions and general intelligence less than compelling, I believe him. However, I also believe that what is required next is a theory of both general intelligence and fluid cognitive functions that articulates the distinction. In the absence of this, more data, particularly of the neuroscience variety, is likely to stall rather than advance progress.

I was pretty much on board with the first third of Blair's target article. He does a good job of summarizing a body of research that at least opens the possibility that there is a case for dissociating "fluid cognitive functions" from psychometric  $g$ . However, the case is not overwhelming, and the road that Blair subsequently takes – to argue that the structure of the brain supports the dissociation – if anything, weakens his case. What the article cries out for is the development of a theory that justifies the dissociation. Such a theory would say something like this: Psychometric  $g$  maps onto cognitive parameters "a, b, c," whereas fluid cognitive functions map onto a different set ("x, y, z"). In the absence of such a theory we are thrown back on the state of the evidence – which is actually rather poor. Let me unpack this a bit.

Nearly all the evidence in favour of a dissociation between psychometric  $g$  and fluid cognitive functions boils down to their less than perfect correlation. I am prepared to suspend

disbelief that the psychometric measures of  $g$  really measure  $g$  (as theoretically unhelpful as that is) because there is a hundred years of convention to go by. But what of the measures of fluid cognitive functions? The first problem is that they are psychometrically much more unreliable. It is little wonder that many studies find that fluid cognitive functions are not perfectly correlated with measures of  $g$ . "Big deal," I hear my psychometrician friends say, "it is just another example of how cognitive/experimental/neuro/developmental psychologists do not know how to develop useful tests – when they get good at it they will find the correlations high enough to support the case that fluid cognitive functions and  $g$  are indistinguishable." But this brings me to the more fundamental problem. How do we know that they are measures of fluid cognitive functions, in the absence of a theory of what those functions are? For example, what does a Stroop task, in its many instantiations, measure (if you care to, substitute your favourite "frontal" task)? Is it a measure of (a) resistance to interference or (b) task switching, or (c) working memory capacity, or maybe even (d) speed of processing? The unhelpful answer is, very likely, all of them. But even leaving that aside, each of these constructs are themselves nearly always free-floating in current research. The constructs usually amount to nothing much more than the operationalization of performance on some tasks and are the subject of a "theory" that contains but one reference – and that is itself (a theory of speed of processing, a theory of working memory capacity, or whatever). I suspect that few other commentators will address this issue. Like the blind spot on our collective retinae, we have become so used to it that it is noticed only by those who specially look out for it. Rarely are such constructs pitted against each other for their explanatory value, and almost never do they feature in a wider theory of the structure of the mind/brain.

Sensing that the distinction, if it is real, might be important, Blair then takes two steps. One is a look for corroboration in neuroscience data, and the other is to argue for a new set of measurements of this distinctive construct (fluid cognitive functions). This reminds me of the very strategy that Arthur Jensen has used in his advocacy of psychometric  $g$  itself (see Anderson [2000], Barrett [2000]; and Jensen [2000a; 2000b] for a discussion). Without knowing what it is that we are looking for, we can either make little sense of some arbitrary data (e.g., positive correlations between IQ and gray matter – how exactly does this speak to the dissociation?), or we resort to forgetting what psychometric  $g$  is supposed to be about. For example, the claim that data from studies of the amygdala, or whatever, show that emotion and stress are important determinants of fluid cognitive functions is relevant only to the dissociation of fluid cognitive functions and psychometric  $g$  if we are discussing the presumed cognitive overlap – for by definition there is no emotion or stress content to psychometric  $g$ . Consequently, this line of evidence and reasoning renders the dissociation vacuous. Further, although new measures of a different construct are a necessary step for science, the new measures that Blair wants to develop seem to be alternative predictors of various real-life behaviours. Therein lies fool's gold – psychometric  $g$  has already cornered the market.

I do believe Blair's central claim (that fluid cognitive functions show some independence of  $g$ ), but I believe this because I have a theory of cognitive functioning that says it is so (see Anderson 2001). Briefly, this theory says that there are two dimensions to  $g$  – one related to individual differences in IQ and dependent on variation in speed of processing, and the other developmental, related to mental age and dependent on the maturation of modular functions, some of which are intrinsically related to "executive functioning" (see Anderson 2005). So I find myself in general agreement with Blair's manifesto and in wholehearted agreement that evidence from psychopathology, neuropsychology (where the studies are driven by theory-based hypotheses), and in particular the study of atypical

and typical development, will be crucial for scientific advance. I also agree with the spirit of his final quote. Were it not for the dissociation of fluid cognitive functions and psychometric *g*, there is a compelling story that relates functioning of the prefrontal cortex and general intelligence, but that “such an explanation would really amount to nothing more than a crafty story and that *g* remains as inscrutable as ever” (target article, sect. 8.1, last para.). Trouble is, it is not the *evidence* cited in this review that illuminates *g*, but a theory that says just how *g* and fluid cognitive functions are different.

## Heterogeneity in fluid cognition and some neural underpinnings

Oana Benga

Department of Psychology, Babes-Bolyai University, Cluj-Napoca 400015, Romania

oanabenga@psychology.ro <http://www.psychology.ro>

**Abstract:** In agreement with Blair, I favor the idea of dissociative patterns in cognitive performance, even more when it comes to development. However, such dissociations are present not only between fluid cognition and general intelligence, but also within fluid cognition itself. Heterogeneity of executive attention, even when indexed with a single paradigm, is further discussed in relation to anterior cingulate cortex.

Blair’s target article raises a critical issue: What should be the key area for diagnosis and intervention in cognitive functioning – particularly when addressing early stages of development? Can the assumption of one and only *g* factor underlying mental abilities really be translated into valuable operational tools, as proposed by traditional psychometrics? The main thesis sustained by the author offers a symmetrically opposed answer – there are patterns in cognitive performance delineating not one, but many factors – which offers itself undoubtedly as a good candidate for assessing individual differences and also for targeting interventions tailored to each individual’s needs.

Yet, there must be some caution in treating fluid cognition unitarily – or more specifically, what Blair calls “*gF*” (that part of fluid cognition independent of *g*). The conceptual interchangeability of fluid cognitive functioning with working memory and executive function(s) as if they are overarching the same construct is useful in contrast to a generic general intelligence, but not really valid when one is trying to clarify the true nature of fluid cognition.

In agreement with the author, I favor the idea of dissociative patterns in cognitive performance, even more so when it comes to development, considering that, as Blair acknowledges, diverse aspects of cognition develop rapidly – but unequally – in early life. During development, dissociations of cognitive functions actually seem to be the rule rather than the exception.

However, I argue that such dissociations are present not only between fluid cognition and general intelligence, but also within fluid cognition itself. The equivalent term for fluid cognition executive function(s) is recognized by many authors as an umbrella concept, encompassing at least working memory, inhibition/inhibitory control/executive attention and flexibility/set shifting (see Miyake et al. 2000).

Inhibitory control/executive attention is an essential construct for both developmental and adult studies. It has a reversed U trajectory, being low in children, high in adults, and low again in elderly people. It has been linked to the developmental progression and further regression of prefrontal/medial frontal structures, and it is thought to be involved in the acquirement of mentalizing abilities. Yet it has proved to be a composite, both theoretically and methodologically (e.g., see the aggregate battery scores proposed by Carlson & Moses 2001). Because

many tasks that are claimed to index inhibitory control have additional requirements, they end up measuring other variables, as well; therefore, I suggest that it is rather difficult, but maybe computationally “cleaner,” to choose computationally (neurally) well-defined tasks when trying to assess and explain inhibitory control, rather than more complex ecologically valid tasks (like many neuropsychological tasks).

I chose the spatial conflict task (Gerardi-Caulton 2000), a modified version of the Simon task, commonly used to measure conflict resolution in adults (Simon & Bernbaum 1990) and having a neural correlate at the level of the anterior cingulate cortex (ACC), as shown by functional magnetic resonance imaging (fMRI) (Fan et al. 2003). My computerized version consisted of presenting two visual stimuli (e.g., a teddy bear and an apple), either on the right or on the left of the screen, with the subject being instructed to respond according to the identity of the stimulus while ignoring the relation between the location of the image and the location of the appropriate response key. Children (2–7 years of age), typically developed, were tested under three experimental conditions: spatial conflict without any other requirement (similar to the adult version of the task), spatial conflict plus working memory load (the subject having to remember which stimulus was assigned to each response key), and spatial conflict plus reward (each correct response being followed by animation of the stimulus). My surprising results support the heterogeneity of executive attention and the presence of distinctive intra-individual patterns, since I found no correlation between incongruent reaction times (RTs) in the three conditions and no correlation between conflict rates (incongruent minus congruent RTs), the longest RTs being present in the reward condition (Benga 2004).

In neural terms, these results could be related either to the involvement of different brain circuits of the prefrontal-limbic network – proposed also by Blair as subserving fluid cognition – the ACC having only the role of conflict monitoring in each, or to different divisions (e.g., dorsal versus ventral [see Bush et al. 2000]) of the ACC involved in different tasks. Although adult neuroimaging studies have shown the activation of the dorsal ACC (thought to be mediated by the dopaminergic system) for spatial conflict tasks without additional requirements, I suggest the involvement of ventral ACC structures, mediated by an opioid system, in reward-related spatial conflict task. (I propose two different biochemical underpinnings to the ACC divisions, inspired by the two biochemical systems described by Luciana 2001.)

ACC divisions have often been explored in terms of their critical role in regulatory behaviors and cognition-emotion interaction, which is also emphasized by Blair. Moreover, they can be integrated in the larger framework proposed here: the amenability of fluid cognition to experience.

An opioid mediation of the ventral ACC could explain, in this line of thought, its vulnerability toward early disruptions of attachment (see Panksepp [2003] for linking attachment to opioids). I have suggested previously (Benga 2001) that dysfunctions in maternal contingency – leading to alterations in attachment – have disturbing, long-lasting effects upon the ACC, and they could explain why institutionalized children show later in life coupled deficits in executive function and social/emotional behavior (Gunnar 2001; O’Connor et al. 1999). According to the ontogenetic scenario suggested by Posner and Rothbart (1998; 2000), in the second half of the first year of life, ACC comes into function, being initially the center of emotional control and later of cognitive control. The correct maturation and functioning of the ACC might depend on contingent external input, offered by a constant caregiver. Animal models (Mathew et al. 2003) link early disruptions of maternal contingency to later biochemical modifications in the ACC: the decrease in the NAA/Cr indicating a decrease of neuronal viability, and the Glx/Cr ratio suggesting the activation of the hypothalamic-pituitary-adrenal axis.

## Prior to paradigm integration, the task is to resolve construct definitions of gF and WM

Damian P. Birney, David B. Bowman, and Gerry Pallier

School of Psychology (A18), University of Sydney, Sydney, NSW, 2006 Australia

damianb@psych.usyd.edu.au davidb@psych.usyd.edu.au

gerrypp@psych.usyd.edu.au

<http://www.psych.usyd.edu.au/staff/damianb/>

**Abstract:** Blair's account, like the intelligence field in general, treats many distinct constructs as if they were practically interchangeable – this is not self-evident. Paradigm integration and rationalization of redundant nomenclature are important for the continued development of understanding. The prior task is to demonstrate where synonymy of constructs across paradigms occurs, and where it fails. We present arguments why this is the case.

Blair's account of the diverse research on fluid cognition and related functions is an ambitious attempt at clarification. Certainly there is a need to dissociate more clearly the various fluid functions from psychometric or mathematical notions of *g*. We concur that *g* has little explanatory power and that the fluid intelligence (gF) framework promises to provide a more informative account of the processes underlying the quintessential aspects of intellectual functioning. As such, we see no value in continuing discussion of *g* other than as a point of historical interest. However, what must not happen is for gF and other constructs that Blair treats as mostly synonymous, such as executive function (EF) and working memory (WM), to be confused and allowed to become increasingly devoid of meaning.

The issue for our commentary has to do with definitions. Definitions tend to be obscured when research paradigms are integrated, because subtle and careful theorising *within* a domain does not always translate well *across* domains. Greater clarity in understanding the issues that Blair presents will not be obtained until more fundamental definitional issues are addressed. For instance, Blair projects and perpetuates confusion in the field's understanding of general intelligence by treating terms such as *g*, psychometric *g*, IQ, and even sometimes *gC*, as synonymous (the latter by equating verbal-scale IQ with general intelligence). Blair's account, like the intelligence field in general, treats many distinct constructs as if they were practically interchangeable – this is not self-evident. Hence, our critique is based as much on the field as it is on this particular review.

The gF-WM-EF issue is a further case in point. gF has developed meaning from within the psychometric domain, where it is common to define constructs not only by what they are, but also by what they are not. Hence, using factor-analytic techniques, gF has been *empirically* defined as the latent trait extracted from a variety of reasoning-dominated tests. This gF trait is related to, but empirically (and therefore theoretically) distinct from, the *gC* latent trait, which is similarly extracted from various tests of (typically verbal based) acculturated knowledge. WM theory was developed within the cognitive-experimental paradigm, mostly using dual-task methodologies to dissociate various storage and processing systems. EF has a more recent history and has been endorsed most actively by cognitive neuropsychology. The tasks used in these related, yet distinct, research programs have been developed with different purposes in mind. Hence, it is not always clear how theorising within one paradigm should be compared and integrated with theorising in another; it is not always clear how core processes identified using different methodologies in different paradigms can be compared (e.g., dual-task or factor-analytic methods); and it is not always clear how task- and paradigm-specific differences might obscure the detection of common underlying processes. Careful investigation is first required to build a common frame of reference between paradigms. Theories must then be

integrated so that *strong* predictions about shared and unique processes can be tested. However, such practices are rare and, in their stead, findings from different paradigms have often been used to bolster validity claims for one paradigm without any real attempt to synthesise theory from the other. We need conceptualisations that are more precise and theoretically "risky" than the typical nomological network of loosely defined theoretical constructs that is pitted against an empirical bed of roughly convergent and divergent correlations (Borsboom et al. 2003; 2004).

The need for careful consideration of definitions is evidenced repeatedly in the literature. For instance, early seminal research cited by Blair appeared to demonstrate that reasoning ability was little more than WM (Kyllonen & Christal 1990). However, this work turned out to be based on a *weak theory* of WM (Conway et al. 2003). That is, the absence of a comprehensive understanding of the processes entailed in WM and the pragmatic approach towards task selection, serve as a caveat in accepting these early signs of synonymy. Despite far-reaching implications of this point for our theoretical understanding of human cognition, and despite due caution at the time by Kyllonen and Christal, this fact has often been overlooked. Research using *stronger* theories based on a more complete understanding of WM has suggested that less than half of the variance in performance on gF tasks can be accounted for by WM capacity (e.g., see Engle et al. 1999b). Crucial to much of Blair's argument is that the tasks used by different researchers to represent variously named constructs are similar in the processes they entail, even if the labelling is different. However, correlations are not sufficient evidence for this (Borsboom et al. 2004). Careful consideration of task characteristics is required because ultimately it is the tasks which provide the operational definition of the latent trait. One must not pass this responsibility off to psychometrics and neglect the importance of careful theory-driven task selection by arguing that factor analysis will distil the uncontaminated error-free latent trait from task-specific characteristics (cf. Colom et al. 2004). Indeed, evidence that the Flynn effect holds in some gF tasks and not others (sect. 3.1 of the target article) indicates that it matters which task(s) one selects as an indicator of gF!

So how are we to proceed through this quagmire? Paradigm integration and rationalization of redundant nomenclature are important for the continued development of understanding. However, the prior task is to demonstrate where *synonymity* of constructs across paradigms occurs, and where it fails. Synonymity means that the processes or constructs operationalised under the different paradigms (gF, WM, or EF, say) are linked to referents that are one and the same – covariation is a necessary condition, but it is not sufficient. gF, as originally conceptualised, is a broad multifaceted factor that psychometrically captures the essence of what is common in tasks requiring, for instance, inductive and deductive reasoning, quantitative reasoning, cognitive flexibility, abstraction of common principles, the development of strategies, and manipulation of mental representations (Carroll 1993). There is no doubt that WM capacity plays some role in determining performance on such tasks. Some argue that what is common is *controlled attention* (Engle et al. 1999a). It also seems clear, however, that when one considers the tasks used to operationalise gF, there is fundamentally more to the conceptualisation than controlled attention. Demonstration of causality, and not simply covariation, must be our goal. This requires an intimate understanding of underlying processes, which in turn requires an intimate understanding of the tasks (Borsboom et al. 2004). Psychometric research has for too long been agnostic to process theories. Blair's account – indeed any account of the field that does not take into consideration definitional differences across studies and across research paradigms – is destined to reflect much more confusion than clarity.

## Exactly how are fluid intelligence, working memory, and executive function related? Cognitive neuroscience approaches to investigating the mechanisms of fluid cognition

Gregory C. Burgess,<sup>a</sup> Todd S. Braver,<sup>a</sup> and Jeremy R. Gray<sup>b</sup>

<sup>a</sup>Department of Psychology, Washington University, Saint Louis, MO 63130;

<sup>b</sup>Department of Psychology, Yale University, New Haven, CT 06520

gburgess@wustl.edu tbraver@wustl.edu

jeremy.gray@yale.edu http://iac.wustl.edu/~ccpweb/

http://pantheon.yale.edu/~scl39/

**Abstract:** Blair proposes that fluid intelligence, working memory, and executive function form a unitary construct: fluid cognition. Recently, our group has utilized a combined correlational–experimental cognitive neuroscience approach, which we argue is beneficial for investigating relationships among these individual differences in terms of neural mechanisms underlying them. Our data do not completely support Blair’s strong position.

Some major tenets of Blair’s position are that fluid intelligence (gF), working memory (WM), and executive function (EF) are isomorphic; that they can be grouped into the unitary construct of *fluid cognition*; and that they can be distinguished from psychometric general intelligence (*g*). Furthermore, he claims that fluid cognition is dependent upon neural structures in lateral prefrontal cortex (PFC) and their interconnections with limbic structures. By extension, this implies that gF, WM, and EF should be equally dependent upon lateral PFC structures. We suggest that such a position, though theoretically appealing, has not been directly tested. Indeed, the existing literature does not support the isomorphism of gF and WM (Kane et al. 2005), a monolithic construct of EF (Miller & Cohen 2001; Miyake et al. 2000; Smith & Jonides 1999), or the exclusive role of lateral PFC in EF processes (Peterson et al. 1998).

We suggest that a cognitive neuroscience approach that integrates experimental and correlational methods (Cronbach 1957) has the most promise for making progress toward understanding more fully the underlying psychological and neural mechanisms that are indexed by these constructs. Processes and neural mechanisms of interest can be manipulated and isolated by using experimental techniques. Measures of specific

processes can be extracted for each individual subject, in terms of both behavior and brain-activity dynamics. Then, those processes can be related to individual difference factors, using correlational approaches. We illustrate the power of this approach with recent findings from our lab.

In these studies, brain activity was monitored with whole-brain functional magnetic resonance imaging (fMRI) while participants performed a demanding WM task (Fig. 1). Activity was examined for different trial types, which varied in EF demands. In the first study (Gray et al. 2003), activity was probed for relationships with individual differences in gF (as measured on the Raven’s Advanced Progressive Matrices). A strong relationship was found between gF and activity during high-interference lure trials in a network of brain regions, including lateral PFC and parietal cortex. This relationship was selective, in that it occurred only for lures, and remained even after controlling for activation on the other trial types. Moreover, the correlation between gF and lure-trial accuracy was statistically mediated by activity in both lateral PFC and parietal cortex. In a recent follow-up study with an independent sample of 102 participants, we found a similar relationship between individual differences in WM span and lure-trial activity across a number of EF-related brain regions (see Fig. 2) (Burgess et al. 2005). Moreover, lure-trial activity within these regions statistically mediated the relationship between gF and WM span, but only partially.

These results have several implications for Blair’s position. First, individual differences in gF are not equivalently sensitive to all aspects of WM function. Instead, strong relationships were present only during one trial type and are apparently specific to one EF component: interference control. Moreover, although WM span and gF are related, the EF of interference control does not fully explain the relationship. Finally, the relationship between gF, WM span, and interference control was explained not only by the activity in lateral PFC, but also within posterior brain regions (parietal cortex). Together, the results clearly suggest that the equation  $gF = EF = WM = PFC$  is too simple to be accurate.

Another study utilizing this approach addressed a theoretical claim, highlighted by Blair, that “evidence for relations between areas of the PFC and ACC [anterior cingulate cortex] and specific aspects of cognition and emotion suggest that a variety of influences, particularly those associated with emotional

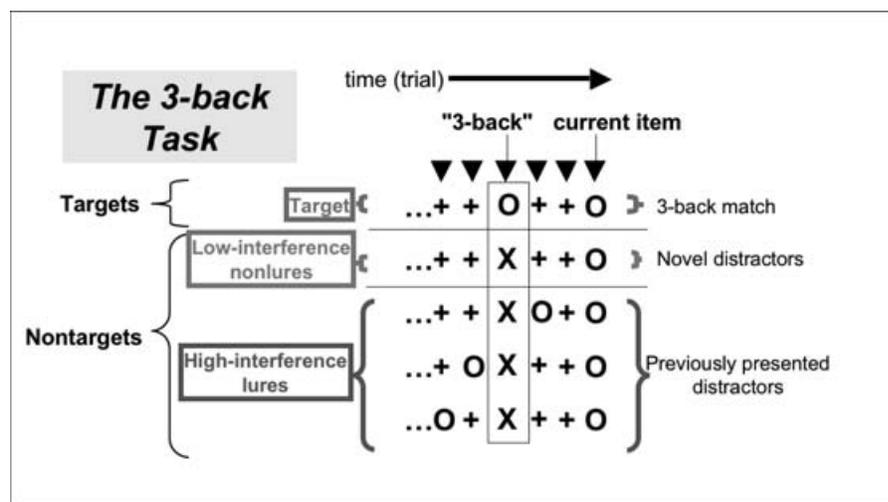


Figure 1 (Burgess et al.). The 3-back working memory (WM) task. A sequential series of items are presented, and judgments are made regarding whether the currently presented item (the *O*) matches the item presented three trials back (*targets*, first row). The task is thought to tap not only into the ability to maintain information in WM (three most recent items), but also to tap into executive function (EF), since WM representations must be updated on each trial and temporally coded. Moreover, the task enables a distinction between low-interference trials (*nonlures*, middle row) and high-interference trials (*lures*, bottom rows). Lures occur when the current item is one that was recently presented (e.g., two or four trials back), but is not the target.

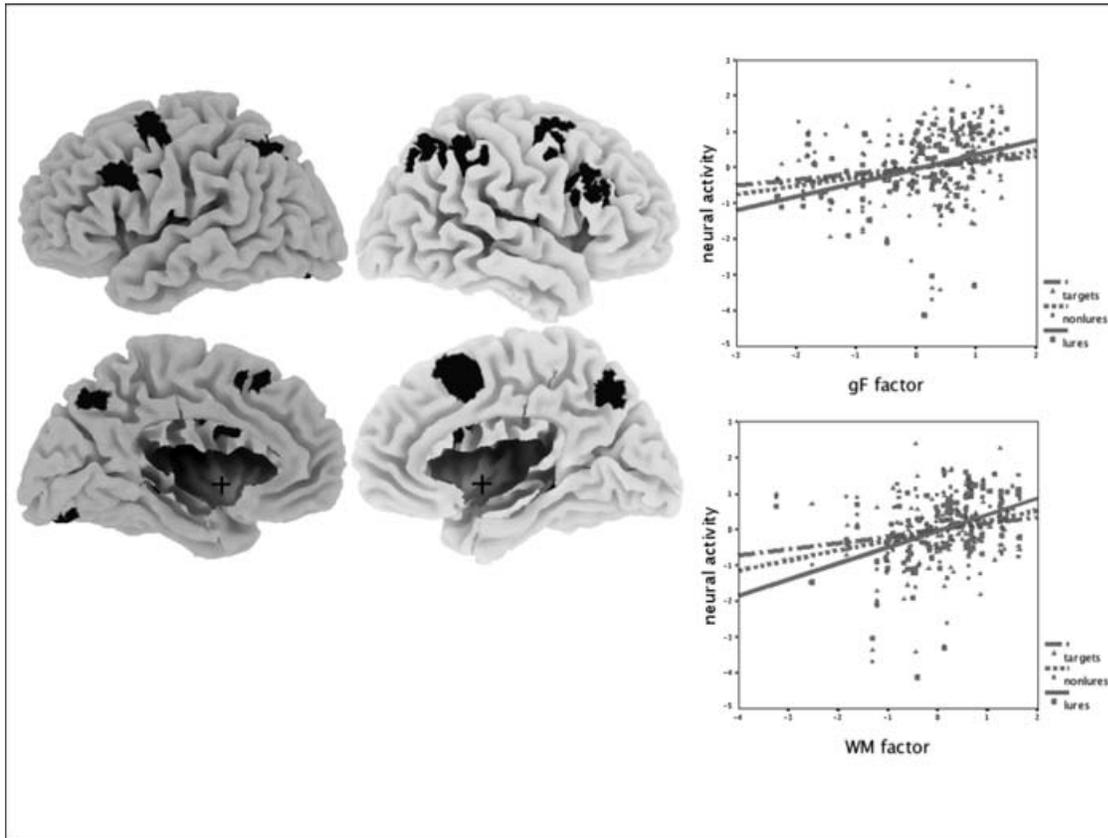


Figure 2 (Burgess et al.). Correlations between neural activity in executive function (EF)-related brain regions and fluid intelligence (gF) and working memory (WM) span. By experimentally manipulating the presence of interference across trial types, we could index the relationships between gF (or WM span) and more specific processes. Lure activity (*solid lines*) correlates strongly with gF (top pane) and WM span (bottom pane), while correlations with nonlure (*narrow dashes*) and target (*wide dashes*) activity are considerably smaller.

arousal and the stress response, may impact fluid cognitive functioning and its apparent similarity to general intelligence” (sect. 2.3, last para.). In the 48 participants from the first study, we tested whether individual differences in affective personality dimensions might impact brain activity in lateral PFC and ACC during 3-back performance in a similar manner as gF (Gray et al., in press). We found that BAS (behavioral activation sensitivity; Carver & White 1994) and extraversion were correlated with activity in lateral PFC and ACC, as predicted by Blair’s account. However, the picture was more complex than this. First, in contrast to gF, the correlations were present across all three trial types, not just lures. Second, the correlations were negative (high BAS/extraversion = less activity), as opposed to the positive correlations with gF. Third, the gF and personality correlations were independent, in that both variables explained lateral PFC activity, even after controlling for the other. Thus, the results suggest that affective individual differences modulate activity in brain regions related to EF, but in a manner distinct from the effects of gF.

Both studies make clear the point that there are relationships among gF, WM, and EF, but that the constructs are not isomorphic. Nevertheless, these results highlight the promise of a combined correlational-experimental approach for more precisely determining the relationships among individual difference constructs. It is our belief that this approach could be extended further to examine other questions raised by Blair, such as the relationship between gF and psychometric *g*, the relationship of gF to distinct EF processes (e.g., conflict detection), affect-cognition interactions, and the mechanisms that relate gF versus psychometric *g* to real-world outcomes (e.g.,

academic success). Critically, the effects of compensatory training or interventions could be more meaningfully evaluated by determining how performance changes relate to changes in underlying brain activity, and whether such changes are linked to variation in gF versus other individual difference constructs, such as psychometric *g*. Such an approach might elucidate the real goal of Blair’s analysis, which is to develop and implement optimal intervention programs for young children facing adversity in order to improve their real-world outcomes. This is a goal that we wholeheartedly support.

#### ACKNOWLEDGMENTS

Research presented within this commentary was supported by NIMH Grant No. R01 66088 and NSF BCS Grant No. 0001908.

### Within fluid cognition: Fluid processing and fluid storage?

Nelson Cowan

Department of Psychological Sciences, University of Missouri, Columbia, MO 65211.

CowanN@missouri.edu <http://web.missouri.edu/~psycowan>

**Abstract:** Blair describes fluid cognition as highly related to working memory and executive processes, and dependent on the integrity of frontal-lobe functioning. However, the literature review appears to neglect potential contributions to fluid cognition of the focus of attention

as an important information-storage device, and the role of posterior brain regions in that kind of storage. Relevant cognitive and imaging studies are discussed.

This target article provides an impressive review of research indicating that fluid cognition is separate from general intelligence and is highly susceptible to environmental, emotional, and specific neurological influences. Fluid cognition is defined as “all-purpose cognitive processing not necessarily associated with any specific content domain and as involving the active or effortful maintenance of information” (sect. 2.1). The term *fluid cognitive functioning* is “used interchangeably to some extent with the terms working memory and executive function” (sect. 2.1) and is said to be associated strongly with frontal-lobe functioning. However, this characterization leaves behind an important part of fluid cognition, involving the use of attention to store information.

In a long-standing model of working memory, Baddeley (1986) described a system in which the storage of information occurred in phonological and visuospatial passive buffers. Executive functions were said to use the stored information to carry out tasks, but did not themselves store information. The phonological store was limited in the duration of the sequence that could be retained, and the visuospatial store supposedly had a similar limit. Both were assumed to hold information automatically, without an investment of effort, for a short time. However, this model did not consider all information in working memory. Stored information actually could include semantic elements, as well as links between elements of different types (e.g., in a group conversation, information about who just said what). It might have to be held in the focus of attention. That type of storage has been taken into account in more recent models (e.g., Baddeley 2000; Case 1995; Cowan 1988; 1995; 1999). An attention limit can account for situations in which the number of elements or chunks that can be held concurrently is severely limited (Cowan et al. 2004; 2005; Garavan 1998; Oberauer 2002).

It does not appear that information in the focus of attention is actually held in the frontal lobes. Although frontal regions are key to the manipulation of information, the storage of information actually appears to take place in posterior regions. Thus, although the frontal regions are more sensitive to the task requirement to manipulate information, posterior regions are more sensitive to the memory load of a task (e.g., see Postle et al. 1999; 2003). Some have proposed that, although the frontal lobes are heavily involved in the control of attention, more posterior, largely parietal areas make up the more important part of the seat or focus of attention, with the retention of attended information (Cowan 1995; Posner & Peterson 1990). For example, Schacter (1989) pointed out that disorders of awareness, such as lateral neglect (inattention to one half of space or one half of each object) and anosognosia (ignorance that one is disabled), are more likely to result from parietal, rather than frontal, lesions.

If the focus of attention is closely associated with activity posterior in the brain and the storage of information also takes place in posterior regions, can we infer that storage itself is attention-demanding? Perhaps. We have examined this question with respect to a visual working memory task in which a haphazard array of small, diversely colored patches is to be compared to a second array that is the same or differs only in the color of one patch (Luck & Vogel 1997). In a well-controlled version of the task, one item in the second array is encircled and the participant has been informed that, if any item in the array changed, it was that one. This task results in excellent performance for arrays of four or fewer patches, and increasingly poorer performance with increasing array sizes. A formula for capacity in the task is based on the assumption that, for items in working memory, the participant correctly indicates whether the cued item has changed or not. If the item is not in working memory, the participant guesses (Cowan 2001). The formula indicates that adults typically keep three or four items in working memory. Neuroimaging and event-related potential studies with this task indicate

that neural activity dependent on the set size and the subject's capacity takes place not in the frontal regions, but in certain posterior regions of the brain (Todd & Marois 2004; Vogel & Machizawa 2004). Moreover, recent evidence indicates that performance in this task is attention-demanding. Overt recitation of a random six- or seven-digit list impairs performance on the visual-array task, especially on trials in which the digit list is recited incorrectly. As controls for other factors, silently retaining a digit list during the retention interval of the visual-array task does not impair performance unless the demands of both tasks are rather large, and neither does the overt recital of a two-digit list or a known telephone number (Morey & Cowan 2004; 2005). Thus, silent verbal maintenance can occur automatically, as can the act of articulation; but recitation of a memory load requires effortful retrieval, and performance on the visual-array task suffers from the consequent drain on attention. Even retrieval of a response in a tone-identification task has this effect on visual-array comparisons (Stevanovski & Jolicoeur 2003).

In the working-memory tasks usually used to show high correlations with intellectual aptitude, storage and processing are combined. However, various types of evidence suggest that, within such tasks, what is important for correlations with aptitude is simply that the processing task prevents rehearsal of the information in storage (see Lépine et al. 2005). Rehearsal may ease the demand for attention. Tasks correlating well with aptitudes also include those that do not have a separate processing component, but that nevertheless preclude rehearsal of the stored information (e.g., the aforementioned visual-array task). A simple digit-span task also correlates with aptitudes in children too young to rehearse the digits (Cowan et al. 2005). All of this suggests that storage, as well as processing, can fall within the camp of *fluid cognition* when attention must be used for storage.

Sometimes, the distinction between storage and processing is unclear. Blair states that “Individuals with prefrontal damage exhibit no deficits on problems whose solution requires holding in mind no relations or only one relation, but exhibit a near inability to solve problems involving two or more relations (Waltz et al. 1999)” (sect. 3.2, para. 1). In this phenomenon (see also Halford et al. 2005), it may take storage to facilitate processing, and it is an open question whether individual differences lie in storage, processing, or both. Fluid cognition is not necessarily all frontal processing.

#### ACKNOWLEDGMENT

This work was carried out with the help of NIH Grant R01 HD-21338.

## Dissecting *g*

Andreas Demetriou

Department of Psychology, University of Cyprus, 1678 Nicosia, Cyprus.  
ademetriou@ucy.ac.cy www.ucy.ac.cy

**Abstract:** Two studies substantiating Blair's main postulates are summarized. The first study showed that fluid cognition, reasoning, and perceived competence about reasoning are separate and equipotent partners in *g*. The second study showed that reasoning, understanding of emotions, and perceived competence about reasoning and emotions partake in the formation of *g*, substantiating Blair's claim that cognition and emotion are linked in the brain.

Blair's main arguments are quite simple. Psychometric *g* and fluid cognition are not identical, and fluid cognition is connected to emotion. I fully endorse both arguments. Psychometric *g* is an intensive construct reflecting whatever is common between all kinds of tasks included in psychometric tests. Most tasks in most tests of intelligence require, in varying proportions, inferential and reasoning processes, problem-solving and self-management skills, domain-specific knowledge, and interest and motivation

to succeed on the test, and, of course, fluid cognition (Demetriou 2004). Fluid cognition sets the frame for the construction and functioning of the other processes but is not identical with them. Emotions regulate how efficiently fluid cognition can be used for the sake of the other processes. Thus, general intelligence is, necessarily, a hyper-construct where all of these processes interact dynamically. In this commentary, I summarize two studies substantiating these postulates.

The first study specifies the relative contribution of fluid cognition, reasoning, and self-awareness in *g* (Demetriou & Kazi, submitted). This study involved 83 participants sampled among 11-, 13-, and 15-year-old adolescents. Three aspects of fluid cognition were examined: speed of processing (e.g., reading color words written in the same ink color), control of processing (e.g., recognizing the ink color of color words where meaning and ink color were incompatible), and working memory (i.e., phonological and visual storage and executive processes). The reasoning tasks addressed four domains: verbal (i.e., verbal analogies and propositional syllogisms), quantitative (i.e., numerical analogies and simple algebraic equations), and spatial reasoning (i.e., mental rotation and the water-level task), and drawing (i.e., draw a scene involving various components). Finally, an inventory probed self-representation in regard to these four domains (e.g., "I immediately solve everyday problems involving numbers").

Figure 1 shows the best-fitting model to the mean scores representing performance on the various tasks. Specifically, the mean score representing speed and the mean score representing control of processing are related to one factor that stands for processing efficiency. The scores representing phonological, visuo-spatial, and executive memory are related to another factor that stands for working memory. Each pair of scores representing performance in or self-representation about a domain of reasoning is related to a separate factor. Therefore, there are four factors standing for performance and four factors standing for perceived competence in each domain. These first-order factors are regressed on three second-order factors. Specifically, the processing efficiency and the working memory factors are regressed on one factor that stands for fluid cognition (*gF*).

The four factors representing performance in the four domains are regressed on another factor, which stands for general reasoning and inferential processes (*g<sub>r</sub>*). Psychometric *g* is very close to this factor. The four self-representation factors are regressed on another factor that stands for general perceived competence (*g<sub>pc</sub>*). Finally, the three second-order factors are regressed on a third-order factor, the "grand *g*" (*G<sub>grand</sub>*). Attention is drawn to the relations between the three second-order factors and *G<sub>grand</sub>*. They are all very high (all > 0.86), clearly suggesting that fluid cognition, inference and problem solving, and self-awareness are distinct, equipotent, and complementary dimensions of general intelligence.

The second study explores the relative contribution of reasoning, understanding and regulation of emotions, and self-representation about these processes to the formation of *g* (Demetriou & Andreou, in preparation). Therefore, this study is related to Blair's claim that intelligence and emotions are interrelated because of corticolimbic connections linking the rational brain (i.e., the prefrontal cortex) with the emotional brain (i.e., the limbic system). This study involved 247 participants, drawn among 10-, 12-, 14-, 16-, and 20-year-olds, who were examined by four batteries: The reasoning battery addressed quantitative (algebraic equations and numerical analogies), causal (isolation of variables and combinatorial reasoning), spatial (mental rotation and coordination of the spatial systems of reference), and social reasoning (understanding the motives and intentions of others). The understanding-of-emotions battery asked participants to construct stories integrating different emotions with relevant events (e.g., "Write a story about an event that makes Michael sad and disappointed and Chris happy and optimistic"). The self-representation battery involved items addressed to the four reasoning domains mentioned above. Finally, the emotions battery addressed emotional self-knowledge (e.g., "I know my emotions very well") and self-regulation (e.g., "I control my emotions"), understanding and regulation of the social aspects of emotions as related to the self (e.g., "I am aware of the non-verbal messages I send to others") and the other (e.g., "I know what others feel by simply looking at them"), a constructive approach to emotionally

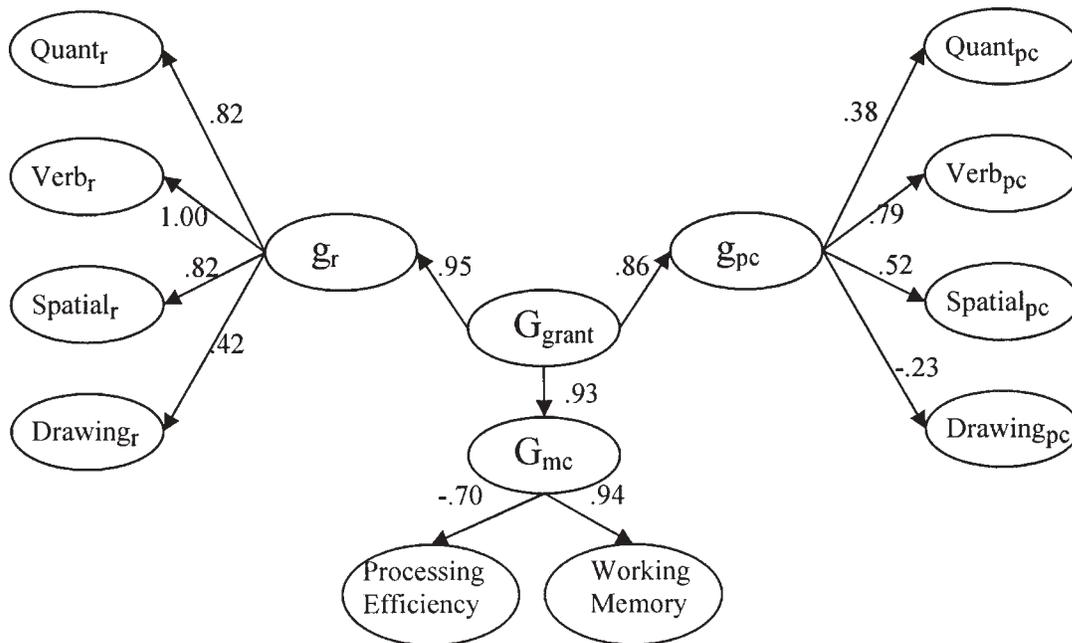


Figure 1 (Demetriou). The best-fitting model to the performance and self-representation attained at the batteries of the first study. Note 1:  $\chi^2(175) = 197.236$ , CFI = .956,  $p = .120$ , RMSEA = .039, and 90% confidence interval = .000 – .065. Note 2: All loadings are significant. [Glossary: G and g stand for general; grand stands for processing underlying general domains of ability; r stands for reasoning; pc stands for perceived competence; mc stands for mental capacity; Quant, Verb, Spatial, Drawing stand for ability in quantitative, verbal, spatial reasoning and drawing.]

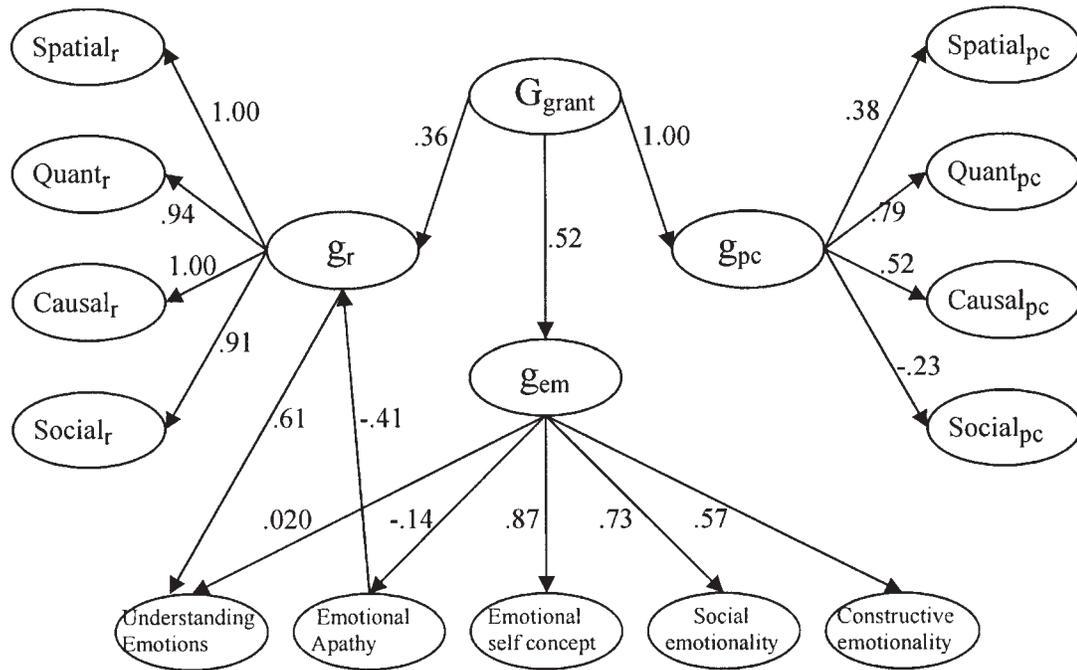


Figure 2 (Demetriou). The best-fitting model to the performance and self-representation attained at the batteries of the second study. Note 1:  $\chi^2(305) = 486.824$ , CFI = .918,  $p < .001$ , RMSEA = .049, and 90% confidence interval = .041 – .057 Note 2: All but the  $g_{em} - Understanding\ emotions$  relations are significant. [Glossary: **em** stands for emotional; for the other symbols, see Fig. 1 caption.]

laden situations (e.g., “When unfairly scolded, I prefer to talk with others and show them that they are wrong”), and emotional apathy (e.g., “I am indifferent to praise”).

Figure 2 shows the best-fitting model to the scores generated by these batteries. There was a first-order factor for each domain of reasoning, a first-order factor for self-representation about these domains, and a first-order factor about the various emotional understanding and self-representation factors. Each set of these three types of factors was regressed on a second-order factor, standing for general reasoning ( $g_r$ ), general perceived competence ( $g_{pc}$ ), and emotional processes ( $g_{em}$ ). Finally, these three second-order factors were regressed on  $G_{grand}$ .

Attention is drawn to the relations between the second-order factors and  $G_{grand}$ . They are .36, 1.0, and .52 for the  $g_r$ ,  $g_{pc}$ , and  $g_{em}$ , respectively. Obviously, this factor, due to the dominance of self-representation items, is highly loaded by self-awareness. It is noteworthy that its relation with  $g_r$  and  $g_{em}$  is significant and in the same range, indicating that self-awareness is a powerful dimension of general intelligence that operates as a liaison between its inferential and its dynamic dimensions. Attention is also drawn to two interesting relations. On the one hand, understanding emotions was strongly connected to  $g_r$  (.61) but negligibly to  $g_{em}$  (.02). On the other hand, emotional apathy was substantially and negatively related with  $g_r$  (-.41). Therefore, the processing of emotions involves a strong inferential component, but, at the same time, inferential processes require emotional involvement to function.

Both models were retested after partialling out the effect of age and found to still fit well. Therefore, the architecture they revealed is genuine to the organization of the various processes rather than the result of possible developmental differences between tasks. This architecture substantiates Blair’s claims that psychometric  $g$  and fluid cognition are not identical and that there are close relations between cognitive and emotional processes. Self-awareness is crucial in sustaining these relations. Therefore, the functional architecture of cognitive and emotional processes uncovered by structural modelling concurs with their organization as suggested by modern research in neuroscience.

## Towards a theory of intelligence beyond $g$

James R. Flynn

Department of Political Studies, University of Otago, Box 56, Dunedin, New Zealand.

jim.flynn@stonebow.otago.ac.nz

**Abstract:** Brain physiology and IQ gains over time both show that various cognitive skills, such as on-the-spot problem solving and arithmetic reasoning, are functionally independent, despite being bundled up in the correlational matrix called  $g$ . We need a theory of intelligence that treats the physiology and sociology of intelligence as having integrity equal to the psychology of individual differences.

Take the ability to solve problems on the spot without a previously learned method as tested by Raven’s or Similarities. When normal people are ranked against one another at a given place and time, those who do better than average on this kind of problem-solving tend to do better on a wide range of cognitive tasks. Thus, this cognitive skill is positively correlated with cognitive tasks, predicts performance on them, and earns the label  $gF$  (fluid general factor). However, when society sets helter-skelter priorities over time – say, emphasizes on-the-spot problem solving and neglects arithmetic reasoning (taxpayers are too silly to pay for good math teachers) – the correlation between this kind of problem solving and other cognitive tasks simply unravels (Flynn 2003). Its predictive potency fades away and, since that is the essence of  $gF$ , it should have a new name. I suggest  $Fpsa$  (fluid problem-solving ability).

The only thing that could prevent society from unraveling the correlational matrix would be brain physiology: a human brain so structured that no single cognitive ability could be enhanced without enhancing all of them. As Blair triumphantly shows, the brain is not like that. When we turn to abnormal brains – those affected by trauma, phenylketonuria, or unusual stress – we find the following: Just as society can pick and choose which mental abilities it wishes to improve, so the brain is sufficiently decentralized that it can pick and choose. Its damaged areas can veto a normal level of  $Fpsa$  while, at the same time,

its undamaged areas can foster normal levels of other cognitive abilities.

Uncorrelated cognitive abilities are significant despite not being bundled up in *g*. People today are better at lateral thinking on the job and better at chess, and more acute in on-the-spot assessment of the quality of political debate, than they used to be (Flynn, in press). Brain-damaged children can keep up at school despite below-average *Fpsa*. If the theory of intelligence is to accommodate uncorrelated abilities, it must transcend *g*. What form would such a theory of intelligence take?

It would have three levels: (1) The B (brain) level, where brain physiology shows how much coordination and how much autonomy functional mental abilities are likely to manifest – what degrees and kinds of problem-solving abilities are likely for both normal and abnormal brains. (2) The ID (individual differences) level, where we assess how cognitive abilities vary from one person to another in a homogeneous social setting, and which shows the extent to which abilities are inter-correlated and predictive of one another in that context. (3) The S (social) level, where evolving and diverse social priorities over time free specific mental abilities from the strictures of *g* (within the limits that the brain allows) and shows them swimming freely from one another and having important consequences. It shows, for example, why America, despite a huge increase in *Fpsa*, has to import foreigners to do its mathematics.

An affection for acronyms suggests a label like the BIDS theory of intelligence. Its focus would be making sense of how various levels are interrelated. At times, one level may show that what happens on another is surprising enough to require explanation. For example, brain physiology (B level) suggests that *Fpsa* is functionally independent of other mental abilities. Yet, when we measure individual differences (ID level), *g* emerges – which is to say individuals who beat the rest of us on one cognitive skill, often outdo us on most cognitive skills. So we have to go back to the brain. Even though different areas are autonomous in the sense that one can function when another is damaged, and in the sense that they can be differentially developed by social change, there must be some overall qualitative factor (the synapses?) – something that makes one normal brain function better on virtually all kinds of problem-solving than another.

At other times, one level may even imply that what is happening on another level is impossible. For example, Jensen (1998, pp. 445–58) analyzed twin studies on the ID (individual differences) level that dramatized the weakness of environment. Indeed, environment appeared so weak that environmental change could not possibly cause huge cognitive gains over a short time – which seemed to imply that IQ gains simply had to have a genetic origin (hybrid vigor) or be spurious. At this point, the Dickens-Flynn model restored coherence to the system by showing that the primacy of genes over environment in individual life history is fully compatible with huge environmental effects as society evolves (Dickens & Flynn 2001a; 2001b).

The *g* theory of intelligence is limited because it views the physiological and sociological levels through its own spectacles. It asks: What elementary cognitive tasks correlate with *g*; what cognitive trends over time correlate with *g* or at least are factor invariant (Wicherts et al. 2004); and so forth. It is as though the physics of moving objects within the earth's gravitational sphere had demanded that astronomy and subatomic physics confine themselves to its model, whereas the way forward was more comprehensive models within which Galileo's equations found their proper place.

The BIDS theory has already paid dividends. Schools teach young children matrices under the delusion that matrix skills and arithmetic reasoning are functionally related. IQ gains over time on the Wechsler Intelligence Scale for Children (WISC) subtests show that the first skill can be greatly augmented with no effect on the second. The relationship is actually correlational. It is as though we observed that good high jumpers tend to be

better-than-average sprinters at any given time – and drew the conclusion that the way to improve high-jump performance was to practice sprinting. We would quickly discover that no high jumper hurtles toward the bar at maximum speed; rather, one gathers the moderate amount of momentum compatible with timing the jump. The correlation between high-jump excellence and sprinting excellence does not signal a functional relationship between the two skills.

A symposium should be convened so that Blair and like-minded thinkers and *g*-men (because *g* is still important on its proper level) can get together and look for a breakthrough in the theory of intelligence. We live in exciting times.

## Early intervention and the growth of children's fluid intelligence: A cognitive developmental perspective

Ruth M. Ford

*Department of Psychology, University of Wales Swansea, Swansea SA2 8PP, United Kingdom*

[r.ford@swansea.ac.uk](mailto:r.ford@swansea.ac.uk)

**Abstract:** From the stance of cognitive developmental theories, claims that general *g* is an entity of the mind are compatible with notions about domain-general development and age-invariant individual differences. Whether executive function is equated with general *g* or fluid *g*, research into the mechanisms by which development occurs is essential to elucidate the kinds of environmental inputs that engender effective intervention.

The debate surrounding the existence of general *g*, and its relation to fluid *g*, bears on the efforts of cognitive developmental psychologists to distinguish between general and specific aspects of children's intellectual growth (Case et al. 2001; Lautrey 2002). Domain-general approaches to development aim to identify cognitive skills that exert a pervasive influence on behavior, even in the presence of specialized abilities with which they interact. In contrast, domain-specific approaches offer a compartmentalized view of the mind by focusing exclusively on the operation of functionally independent modules.

A variety of domain-general accounts exist, some of which have advocated components of executive function, such as working memory, as prime candidates for explaining broad, age-dependent gains in intellectual ability (e.g., Case 1992). Despite their physiological localization in the frontal regions of the brain, executive functions could thus constitute a driving force in cognitive development that has ramifications for all mental activities. Recent years have seen major advances in the understanding of executive function and its role in the emergence of consciousness (Zelazo 2004), agency (Russell 1999), and self-regulation (Carlson 2003). Not only does executive function undergo marked improvements as children grow older, the distinction between "hot" and "cool" executive function seems well placed to provide new insights into the development of social cognition and behavior (Zelazo et al. 2005).

If executive function is equated instead with fluid *g*, then general *g* might correspond with some other aspect of development such as global processing speed (e.g., Kail 1991) or, alternatively, a dimension of intelligence that is not related to development at all. As an example of the latter approach, the minimal cognitive architecture model of intelligence and development (Anderson 2001) views intelligent behavior as a product of both age-invariant and developmental mechanisms. The model assumes that age-invariant mechanisms are responsible for individual differences in intellectual ability within a particular developmental level and are determined mainly by heredity. In contrast, it sees developmental mechanisms as involving the maturation of dedicated information-processing

modules, including executive function, that are more amenable to environmental influences.

Uniformly, theories of cognitive development posit that information provided by the environment is necessary for cognitive growth and, thus, that experiential factors have an impact on developmental outcomes. The assumption is that, whereas heredity might place limits on a child's potential achievements, it is the environment that determines the extent to which this potential is realized (Sternberg 2002). Relative to the extensive study of the heritability of general *g*, there has been little investigation of whether specific cognitive functions are differentially sensitive to environmental stimulation (Grigorenko & Sternberg 2003). To distinguish between varieties of domain-specific development, however, is to acknowledge the possibility that some cognitive functions exhibit greater plasticity than others (Flavell et al. 2002).

Language and executive skills in young children are affected more severely by low socio-economic status than are other measures of intellectual ability (Noble et al. 2005), suggesting they represent vulnerable aspects of cognitive development that might profitably be targeted by intervention. Importantly, as reviewed in the target article, what limited evidence is available indicates that the development of executive function during early childhood is probably responsive to nurture. Such evidence bolsters the recommendation that early compensatory education programs for disadvantaged children should strive not only to impart knowledge, but to foster those thinking skills that enable children to use their knowledge effectively.

With the aim of intervention in mind, an important agenda for future research is to examine the basic mechanisms driving cognitive development (i.e., an emphasis on the *how* rather than *what* of development; Case & Mueller 2001; Siegler 1996) to improve the efficacy of such programs. Potentially, the goal of improving executive function in children with low socio-economic status could be accomplished by encouraging their parents to interact with them in ways that promote language acquisition and self-regulation. Gauvain (2001) argued that social processes qualify as mechanisms of intellectual growth on the grounds that they teach children strategies for acquiring and manipulating knowledge, for choosing between alternative courses of action, and for deploying their knowledge and skills in new contexts. From a Vygotskian perspective, children learn to think and to regulate their behavior by internalizing the language of more competent members of their community during social interactions that involve problem solving. The theory thus assumes that children experience new ways of thinking first collaboratively and then on the individual plane (Vygotsky 1978). The view that social processes are integral to cognitive development is compatible with Siegler's (1996) concepts of variability and choice as mechanisms of learning, as well as the hypothesized role of private speech in aspects of executive function (Carlson 2003).

Those of us involved with early intervention know that it is costly and time consuming, and often regarded less favorably by funding bodies than is research deemed "pure" rather than "applied." In concluding, I therefore want to emphasize that the use of longitudinal methods in early intervention presents a prime opportunity for addressing fundamental questions about the nature of children's cognitive development. Longitudinal research has the potential to shed light on causal mechanisms in cognitive development, for example, those underpinning the close relations between executive skills, language, and theory of mind (Carlson et al. 2004). By incorporating precise manipulations of children's intervention experiences into longitudinal assessments of their cognitive and social/emotional functioning it should be possible to elucidate both the development of different aspects of intelligence during early childhood and the relations between emotion and higher-order cognition that traditionally have been neglected by cognitive developmental researchers.

## There is more to fluid intelligence than working memory capacity and executive function

Dennis Garlick and Terrence J. Sejnowski

Computational Neurobiology Laboratory, Salk Institute, La Jolla, CA 92037.

dgarlick@salk.edu terry@salk.edu <http://www.cnl.salk.edu>

**Abstract:** Although working memory capacity and executive function contribute to human intelligence, we question whether there is an equivalence between them and fluid intelligence. We contend that any satisfactory neurobiological explanation of fluid intelligence needs to include abstraction as an important computational component of brain processing.

Understanding fluid intelligence is a fascinating problem for behavioral and brain research. Fluid intelligence problems such as Raven's Progressive Matrices, Number Series, and Word Analogies involve presenting participants with problems that they are unlikely to have seen before. Successful performance cannot then be attributed to any simple learning mechanism based on previously seeing and memorizing the correct answer to the exact same problem. However, despite this, humans are able to solve these kinds of problems, suggesting that fluid intelligence is an important construct for assessing the human capacity to perform successfully across a wide range of situations. This is also supported by psychometric findings suggesting that fluid intelligence is the best predictor of performance in situations that involve human intelligence, including performance at school, at university, and in cognitively demanding occupations (Gottfredson 1997).

Understanding the nature of fluid intelligence has been a profound problem for psychometric intelligence research. Indeed, even recent reviews admit that we still have no satisfactory explanation of what causes differences in fluid intelligence (Brody 1992; Jensen 1998; Neisser et al. 1996). Blair suggests an answer, using the constructs of working memory capacity and executive function (see also Kane & Engle 2002). Indeed, the notions that working memory capacity and executive function are explanations of fluid intelligence are plausible. After all, the solution of fluid intelligence tasks undoubtedly involves the use of working memory. Similarly, executive functions are the result of an evolutionary recent brain area, so equating the operation of this brain area with fluid intelligence, again a capacity that is most evident in humans, would again seem plausible. It is also logical to identify fluid function with the prefrontal cortex, an area that is notable for playing a control function and not having direct connections with sensory input.

However, though the answer Blair gives has been suggested in the past, it is endorsed by relatively few current researchers. One reason for the lack of support for a relationship between fluid intelligence (*gF*) and working memory and executive function is that tasks that assess working memory and executive function often do not reflect *gF*. For instance, tasks developed according to working memory principles often do not correlate with *gF*. Researchers arguing for a working memory capacity explanation of intelligence have then sought to strengthen this relationship by simply making working memory tasks involve the manipulation and transformation of information, elements that are commonly involved in fluid intelligence tasks (see Kyllonen & Christal 1990). However, this would then suggest that it is not working memory capacity per se that is leading to the correlations between these tasks and fluid intelligence, and leads to a circular argument. Unsworth and Engle (2005) also found that a working memory capacity task predicted performance equally on Raven's problems that varied based on difficulty, memory load, and rule type. This again suggests that it is not working memory capacity per se that mediates the relationship between working memory capacity and fluid intelligence. Similarly, performance on executive function tasks often are not related to performance on fluid

intelligence tasks. Blair describes the Wisconsin Card Sorting Task (WCST), a well-known measure of executive function, as a fluid intelligence measure, even though the WCST is not known to be an indicator of fluid intelligence. The relationship between prefrontal cortex and fluid intelligence is again complex. Only the most difficult Raven's problems show activation in the prefrontal cortex (Prabhakaran et al. 1997), even though the easier Raven's problems are still measures of fluid intelligence. This indicates that fluid intelligence does not depend on something that is specific to the prefrontal cortex.

Our concern is that Blair is then making the supposed fit between fluid intelligence and working memory capacity and executive function by redefining fluid intelligence in working memory and executive function terms. Evidence that then supports this correspondence is selectively referenced, while evidence that contradicts this framework is neglected. This is of crucial importance. When Blair claims to find a dissociation between fluid intelligence and *g*, we suspect that he is in fact finding a dissociation between fluid intelligence and working memory capacity/executive function. Indeed, while criticizing current research for ignoring relevant distinctions between cognitive processes, Blair is in fact guilty of this himself when he chooses to lump the constructs of *gF*, working memory, and executive function into the one construct. It may be that cortical damage compromises executive function while fluid functions remain largely intact, such as in the case of the absentminded professor. Only by using measures that assess all of these functions can we hope to understand their interplay. Simply assuming at the outset that fluid intelligence, working memory capacity, and executive function are the same construct is likely to mean that effects are missed that would be detected if the constructs were recognized as being distinct.

Even more problematic for the proposed neurobiological model of fluid intelligence is that it makes no mention of abstraction, even though, unlike working memory capacity and executive function, all fluid intelligence problems involve abstraction. Abstraction is also recognized as being the hallmark of intelligence (e.g., Snyderman & Rothman 1987). Until theories of fluid intelligence address this issue of abstraction, they will continue to fail to provide an explanation that enables us to actually understand the nature of intelligence. Examining localization in the brain is likely to be of only limited help at best in this endeavor. Different areas of the cortex are likely to be important for representing different abstract properties. This does not contradict the notion of a general fluid factor, as these different areas may depend on a common mechanism to extract abstract information out of the environment (Garlick 2002). Rather, the answer is likely to lie in understanding how the brain computes abstraction. Unfortunately, little is known about the neural basis for abstraction. This needs to be a goal of future research.

#### ACKNOWLEDGMENTS

Terrence J. Sejnowski is supported by the Howard Hughes Medical Institute, the Salk Institute for Biological Studies, La Jolla, California, and the Division of Biological Sciences, University of California, San Diego, La Jolla, California.

### Working memory, executive function, and general fluid intelligence are not the same

Richard P. Heitz,<sup>a</sup> Thomas S. Redick,<sup>a</sup> David Z. Hambrick,<sup>b</sup> Michael J. Kane,<sup>c</sup> Andrew R. A. Conway,<sup>d</sup> and Randall W. Engle<sup>a</sup>

<sup>a</sup>School of Psychology, Georgia Institute of Technology, Atlanta, GA 30332;

<sup>b</sup>Department of Psychology, Michigan State University, East Lansing, MI.

48824; <sup>c</sup>Department of Psychology, University of North Carolina, Greensboro,

NC 27402-6164; <sup>d</sup>Psychology Department, Princeton University, Princeton University, Princeton, NJ 08544.

richard.heitz@psych.gatech.edu    psychology.gatech.edu/renglelab  
 gtg458n@mail.gatech.edu    hambric3@msu.edu  
<http://psychology.msu.edu/people/faculty/hambrick.htm>  
 mjokane@uncg.edu  
<http://www.uncg.edu/psy/graduateprogram/cognitive/faculty/mjk-index.html>  
 aconway@Princeton.edu  
<http://webscript.princeton.edu/~psych/psychology/research/conway/index.php>  
 randall.engele@psych.gatech.edu    psychology.gatech.edu/renglelab

**Abstract:** Blair equates the constructs of working memory (WM), executive function, and general fluid intelligence (*gF*). We argue that there is good reason not to equate these constructs. We view WM and *gF* as separable but highly related, and suggest that the mechanism behind the relationship is controlled attention – an ability that is dependent on normal functioning of the prefrontal cortex.

Blair's target article addresses an issue that is of fundamental importance to understanding higher cognitive functioning: What is the relationship between the constructs of fluid cognition and general intelligence? Blair addresses this issue while trying to integrate the fields of behavioral psychology, psychometric intelligence, and cognitive neuroscience – fields that tend to employ different types of tasks while discussing identical constructs. We argue that although this is a valiant and much-needed effort, more attention must be given to the operational definition of *fluid cognition*. Specifically, we believe that working memory, executive function, and general fluid intelligence are not the same.

In his review, Blair examines the relationship between what he calls “fluid cognition” and general intelligence. However, we argue that five separate constructs are considered: working memory (WM), executive function (EF), general intelligence (*g*) and, related to *g*, general fluid intelligence (*gF*) and general crystallized intelligence (*gC*). Critically, Blair equates WM, EF, and *gF* under the label of “fluid cognition.” Unfortunately, there is good reason *not* to equate these three constructs. First, although some evidence suggests that WM and fluid intelligence are identical (e.g., Colom et al. 2004; Kyllonen & Christal 1990), a great deal more suggests that, although strongly related, WM and *gF* are clearly not isomorphic. Essentially, if the constructs were indistinguishable, the correlations between latent factors representing these constructs would be consistently near 1.0; in reality, they are closer to .72, indicating approximately 50% shared variance between them (Kane et al. 2005; see also Ackerman et al. 2005; Conway et al. 2003; Heitz et al. 2004).

Second, there is evidence to suggest that WM and EF are separable, despite research showing that they, also, are correlated. For example, tasks designed to measure EF such as Tower of Hanoi, Wisconsin card sorting, random-number generation, and Stroop compose a latent factor that is separable from those of WM tasks (Miyake et al. 2000; 2001). Additionally, switch costs from the task-set switching paradigms (often used as a measure of EF) do not correlate well with WM measures (Kane & Engle 2004; Oberauer et al. 2003); however, there is some evidence to suggest that the prototypical task-switching paradigm, itself, is not a measure of EF (Logan & Bundesen 2003).

To this point, we have argued that WM is not isomorphic with *gF*, and that WM and EF are related but dissociable. By this view, equating these constructs in an effort to understand *g* is problematic. Equally problematic is the fact that *g* and *gF* are very highly correlated, and some have argued that they are virtually identical (Gustafsson 1984). Therefore, instead of focusing our own research on *g*, we have correlated measures of *gF* such as Raven's Progressive Matrices and the Cattell Culture Fair Test with measures of WM such as reading span and operation span (Engle et al. 1999; Kane et al. 2004). We argue that these efforts essentially target the same issue that Blair is concerned with, given that our definition of WM and Blair's definition of fluid cognition are virtually identical. With this in mind, we address research relating individual differences in WM capacity to individual differences in *gF*.

That WM correlates positively with gF is not controversial. What is under debate is the mechanism for this correlation. Research suggests that one common link is prefrontal cortex (PFC) functioning (Kane & Engle 2002). For example, human and nonhuman primate studies find significantly reduced WM task performance with PFC lesions that are not observed with more posterior lesions (Kane & Engle 2002). Similarly, patients with PFC lesions demonstrate a marked deficit in gF-loaded task performance compared to healthy controls (Duncan et al. 1995).

To be specific, our view is that differential functioning of the PFC brings about individual differences in executive attention control. According to our view, this general attention ability should reveal itself not only in high-level cognitive tasks such as those designed to measure gF, but also in fairly low-level tasks, provided that the task requires effortful attention control. In one of the most striking examples of this, Kane et al. (2001) (see also Unsworth et al. 2004) found that individuals high in WM capacity (“high spans”) performed better than those low in WM capacity (“low spans”) in a selective orienting task. Specifically, in the antisaccade condition, subjects had to resist reflexive orienting toward a flashing cue and instead execute a saccade in the *opposite* direction. Low span subjects committed more errors, and, even when their saccade was in the correct direction, they were slower to do so. This result stands in contrast to performance in the prosaccade condition, where both high and low WM span subjects were equally able to orient *toward* the flashing cue.

In another such low-level task, Heitz and Engle (submitted) had subjects perform the Eriksen flanker paradigm. Subjects were to respond with one hand if the center letter was H and with the other hand if the center letter was S. On compatible trials, all the letters were identical (e.g., SSSS). However, on incompatible trials, the center letter was surrounded by response-incompatible letters (e.g., SSHS). Thus, to perform this task effectively, subjects had to focus their attention (for example, by constraining their attentional allocation) on the center letter in an effort to filter the surrounding distractor letters. Heitz and Engle (submitted) found that low spans were slower to perform this visual-attention filtering than were high spans. Again, no span differences were evident in the compatible trials, when attentional constraint was unnecessary.

These low-level tasks, though unrelated on their surface to traditional WM-span tasks such as reading span, reliably dissociate low and high WM span participants. This, along with our structural equation modeling studies, suggest that what is important for high-level and low-level cognitive functioning is the ability to control attention, whether this serves the purpose of filtering distractor letters in the visual field or maintaining a list of letters in a distracting environment. Although we do not yet know exactly how this is important for fluid intelligence, the strong relationship between WM and gF, as well as a shared reliance on the PFC, support a view implicating attentional control. Our continued efforts are directed at examining this issue in detail.

## Clarifying process versus structure in human intelligence: Stop talking about fluid and crystallized

Wendy Johnson and Irving I. Gottesman

Department of Psychology, University of Minnesota, Minneapolis, MN 55455  
john4350@umn.edu igottesman@mn.rr.com

**Abstract:** Blair presumes the validity of the fluid-crystallized model throughout his article. Two comparative evaluations recently demonstrated that this presumption can be challenged. The fluid-crystallized

model offers little to the understanding of the structural manifestation of general intelligence and other more specific abilities. It obscures important issues involving the distinction of pervasive learning disabilities (low general intelligence) from specific, content-related disabilities that impede the development of particular skills.

The dominant theoretical model of the structure of human intellect in the psychometric tradition is based on the theory of fluid and crystallized intelligence. Developed initially by Cattell (1943; 1963) and elaborated in greater detail by Horn (1976; 1985; 1998), the theory of fluid and crystallized intelligence distinguishes these two abilities. Fluid ability is demonstrated by solving problems for which prior experience and learned knowledge are of little use. It is measured best by tests having little scholastic or cultural content, such as verbal tasks that rely on relationships among familiar words, or perceptual and figural tasks. Crystallized ability reflects consolidated knowledge gained by education, access to cultural information, and experience. An individual's crystallized ability originates with fluid ability but is developed through access to and selection of learning experiences. Consequently, among people of similar educational and cultural background, individual differences in fluid ability are thought to influence individual differences in crystallized ability. Yet, persons from different cultural backgrounds with the same level of fluid ability are predicted to differ in crystallized ability. This is the theoretical basis for arguing that many intelligence tests are culturally biased.

As conceived initially, fluid-crystallized theory was used to argue against the existence of general intelligence (Cattell 1971; Horn 1989), based on the belief that the higher-order general intelligence factors arising from different batteries of tests would vary. For three widely known test batteries, however, this belief was unfounded (Johnson et al. 2004). In more recent years, Carroll's (1993) monumental and systematic exploratory factor analysis of more than 460 data sets has built some consensus around a three-strata hierarchical model with general intelligence at the highest stratum, and fluid and crystallized abilities prominent among the more specialized abilities in the second stratum. This model effectively synthesizes the ideas of intelligence researchers over the past 100 years.

Blair's creative synthesis makes clear that the descriptive accuracy of this model has been presumed in designing studies spanning the domains of psychology, as well as in designing intelligence assessment tools. It is also assumed by Blair. Surprisingly, received wisdom has not been subject to empirical scrutiny in the form of comparative assessment, despite the existence of other models for the structure of intellect. Two comparative evaluations using modern confirmatory factor-analytic techniques, however, demonstrated clearly that the fluid-crystallized model provides an inaccurate description of the structure of human intellect (Johnson & Bouchard 2005; in press). Vernon's (1964; 1965) more content-based verbal-perceptual model provides greater descriptive accuracy, which is further enhanced by the addition of a factor representing image rotation.

The fluid-crystallized model as extended by Carroll (1993) differs from the Vernon (1964; 1965) model in the definitions of the concepts of fluid and crystallized intelligence and verbal and perceptual abilities. Clarity about these definitions is complicated by the fact that many researchers have tended to conflate fluid intelligence with perceptual abilities, and crystallized intelligence with verbal abilities. The two sets of terms do overlap to a substantial degree, but they can also be distinguished in a straightforward way. As noted, learned knowledge and skill contribute little to manifestations of fluid intelligence but extensively to manifestations of crystallized intelligence. Both Cattell (1971) and Horn (1989) were clear that this distinction in the role of experience applies across content boundaries. In contrast, Vernon's verbal and perceptual abilities follow content areas. Thus, tests involving the explicit use of pre-existing perceptual knowledge would contribute to crystallized intelligence, but not to verbal ability. Further, tests that involve abstract reasoning

with factual knowledge would contribute to both fluid and crystallized intelligence, but such tests would not contribute to perceptual ability. The structure of ability follows the verbal-perceptual outline rather than the fluid-crystallized outline (Johnson & Bouchard 2005; in press), rendering the controversy surrounding the question of the equivalence of fluid and general intelligence moot.

Psychometric models of the structure of intellectual ability offer objective and rigorous frameworks for studying genetic (Gottesman 1997; Plomin & Craig, in press) and epigenetically mediated neurobiological endophenotypes and processes (Gottesman & Gould 2003; Weaver et al. 2004), as well as insight into the relative accuracy of the measurement tools we use to assess the ability of individuals and to predict their success in educational and occupational domains. The research Blair describes highlights the limitations of the fluid-crystallized model in addressing these purposes. Paper-and-pencil tests of ability are blunt measurement tools. Performance on any task always reflects learned behavior to at least some degree. People also likely differ in their prior exposure to any task as much as they do in innate ability to address any truly novel task. Consequently, it is never possible to measure innate ability per se, and there is always variance in the degree to which innate ability is reflected in individual test scores. In addition, most problems can be solved using multiple strategies, making it difficult to be sure that any specific task measures any specific ability. Nevertheless, it is clear that the variance common to even a relatively small battery of such tests taps a general intellectual ability with substantial relevance to a wide variety of life outcomes (Gottfredson 1997; Jensen 1998; Lubinski 2004). Blair raises important questions related to the biological development of this general ability in the context of emotional regulation and environmental stress, but we will be able to address these questions more fruitfully by separating the process of development from the structures developed.

Jensen (1998, p. 95) nicely distinguished between processes and structures in their implications for understanding intellectual performance. We may be able to use fluid-crystallized theory to understand how intellectual performance emerges in the individual, but understanding the structural manifestation of general intelligence and other more specific abilities requires comparison across individuals in a systems biology context (Grant 2003). Fluid-crystallized theory has little to offer in this regard. It may even delay the resolution of important issues involving the distinction of pervasive learning disabilities (low general intelligence) from specific, content-related disabilities that impede the development of particular skills. These specific disabilities also tend to follow Vernon's (1965) hierarchical structure of general intelligence supplemented with specific verbal and perceptual abilities, further supplemented with image-rotation ability.

## Some considerations concerning neurological development and psychometric assessment

James C. Kaufman<sup>a</sup> and Alan S. Kaufman<sup>b</sup>

<sup>a</sup>Department of Psychology/Learning Research Institute, California State University, San Bernardino, CA 92407; and <sup>b</sup>Yale School of Medicine, Yale Child Study Center, New Haven, CT 06520-7900.

jkaufman@csusb.edu alanadeen@att.net

<http://psychology.csusb.edu/faculty/jkaufman/index.html>

**Abstract:** Blair makes a strong case that fluid cognition and psychometric *g* are not identical constructs. However, he fails to mention the development of the prefrontal cortex, which likely makes the Gf-*g* distinction different in children than in adults.<sup>1</sup> He also incorrectly states that current IQ tests do not measure Gf; we discuss several recent instruments that measure Gf quite well.

Blair's target article makes a strong case that fluid cognition and psychometric *g* are not identical constructs. Indeed, these constructs are clearly dissimilar for adults, a notion supported for years by a wealth of aging research generated by Horn and Cattell's (1966) constructs of fluid (Gf)<sup>1</sup> and crystallized (Gc) intelligence. Dramatically different growth curves have been demonstrated for Gf and Gc across the adult life span for numerous adult tests (e.g., Kaufman 2001). Blair includes aging research on the Horn-Cattell constructs as one piece of evidence for the distinctiveness of Gf and *g*, and we agree that this one argument, per se, is stronger than any factor-analytically based psychometric argument that Gf and *g* are virtual identities.

Blair's evidence for the distinctions between Gf and *g* for children, though strongly reasoned and diverse in its breadth, is less compelling than the evidence for adults. Blair appropriately discusses the key role played by the prefrontal cortex (PFC) in fluid cognitive functions, but fails to mention or consider the development of these functions in children. As Golden (1981) indicates, it is not until about ages 11–12, on average, that “the prefrontal areas of the brain that serve as the tertiary level of the output/planning unit develop” (p. 292). This level corresponds to the onset of Piaget's stage of formal operations (Inhelder & Piaget 1958) and the emergence of Luria's (1970) Block 3 planning abilities.

The identification of Gf factors in groups of normal children also has a distinct developmental component. These factors do not emerge as separate constructs until about age 6 or 7 (Elliott 1990; Kaufman & Kaufman 2004). Therefore, the relationship between Gf and *g* in children is likely to be a different phenomenon for children below age 6, for those between 7 and 11, and for adolescents. As multifaceted in scope as Blair's analysis was, his conclusions for children should be treated as tentative pending more thorough developmental analyses.

One other area of Blair's review that was relatively weak was his apparent lack of awareness of the contemporary psychometric scene regarding the assessment of fluid cognition, especially in children. He cited a 15-year-old source (Woodcock 1990) and an 8-year-old source (McGrew 1997) to document “the limited assessment of gF currently available in many widely used intelligence tests” (sect. 4.1, para. 3) and to state that these tests “disproportionately assess crystallized skills and domains of intelligence associated with opportunity for learning” (sect. 7.1, para. 2).

Those claims are simply not true. Tests that deemphasized *g* and provided measurement of fluid cognition began to be published shortly after Woodcock's (1990) article went to press, and have proliferated since McGrew's (1997) chapter was published. The latest versions of the Wechsler and Binet tests are joined by many other well-normed, psychometrically sound, cognitive ability tests that minimize the importance of *g*, emphasize the assessment of multiple abilities and measure fluid cognition. Listed chronologically, the following tests all provide excellent measurement of fluid cognition:

1. *Differential Ability Scales* (DAS [Elliott 1990]), 2½–17 years; includes three scales for school-age children, one of which is a Nonverbal Reasoning Scale that measures Gf (Keith 2005).

2. *Kaufman Adolescent and Adult Intelligence Test* (KAIT [Kaufman & Kaufman 1993]), 11–85+ years; includes two scales named Crystallized Intelligence and Fluid Intelligence; two subtests (Mystery Codes and Logical Steps) are considered excellent measures of Gf (Flanagan & Ortiz 2001).

3. *Wechsler Adult Intelligence Scale*, 3rd edition (WAIS-III [Wechsler 1997]), 16–89 years; added a measure of Gf (Matrix Reasoning) to the Performance Scale, a measure of working memory (Letter-Number Sequencing), and a separate Working Memory Index.

4. *Cognitive Assessment System* (CAS [Naglieri & Das 1997]), 5–17 years; includes four scales derived from Luria's theory, one

of which is called Planning Ability that measures the planning functions of the PFC.

5. *NEPSY: A Developmental Neuropsychological Assessment* (Korkman et al. 1998), 3–12 years; developed from Luria's theory and includes five domains, including Attention/Executive functions.

6. *Woodcock-Johnson*, 3rd edition (WJ III [Woodcock et al. 2001]), 2–95+ years; developed from Cattell-Horn-Carroll (CHC) theory; measures seven cognitive factors, including Fluid Reasoning.

7. *Wechsler Preschool and Primary Scale of Intelligence*, 3rd edition (WPPSI-III [Wechsler 2002]), 2½–7 years; added three measures of fluid reasoning – Matrix Reasoning, Word Reasoning, and Picture Concepts.

8. *Stanford-Binet Intelligence Scales*, 5th edition (SB5 [Roid 2003]), 2–85+ years; developed from CHC theory and includes five scales, including Fluid Reasoning.

9. *Wechsler Intelligence Scale for Children*, 4th edition (WISC-IV [Wechsler 2003]), 6–16 years; added three measures of fluid reasoning – Matrix Reasoning, Word Reasoning, and Picture Concepts – and one measure of working memory (Letter–Number Sequencing); eliminated verbal and performance IQs in favor of four indexes.

10. *Kaufman Assessment Battery for Children*, 2nd edition (KABC-II [Kaufman & Kaufman 2004]), 3–18 years; developed from a blend of CHC and Luria theories; includes five scales, including one labeled Planning/Gf intended to measure the PFC Block 3 functions from Luria's theory and fluid reasoning ability from CHC theory.

Consequently, Blair's following statement is false: "As measures of crystallized skills, currently available assessment batteries will provide a limited perspective on the cognitive abilities of children . . . [They] will not really be able to address [fluid aspects of cognition]" (sect. 7.1, para. 3).

In fact, excellent measures of children's fluid cognition are readily available. The newer breed of intelligence test decidedly does *not* overemphasize crystallized abilities. Instead, the focus has shifted to fluid reasoning, planning ability, the ability to learn new material, and working memory. As Blair urges, much research needs to be done. We agree. But it is important to note that appropriate tests of fluid cognition are ready and waiting.

In addition, there is psychometric evidence with recent tests that suggests strong overlap between measures of fluid ability and *g*. Keith (2005) applied the technique of hierarchical confirmatory factor analysis (CFA) to several data sets. For the DAS, the fluid factor correlated .98 with *g* in one study and 1.0 in another. Kaufman and Kaufman (2004) applied Keith's CFA approach to the KABC-II and observed 1.0 correlations between fluid cognition and *g*.

These psychometric findings do not mean that fluid cognition and psychometric *g* are identical constructs. Blair has cogently argued that a wealth of other data needs to be integrated with the psychometric results to reach any reasonable conclusions about this relationship. However, we believe that more research needs to be done with samples of children (not adults) before reaching the firm conclusion that the two constructs are distinct.

#### NOTE

1. Whereas Blair used the abbreviation "gF" to denote fluid cognition, we have opted to use "Gf," which is the abbreviation used by Cattell-Horn-Carroll (CHC) theorists and researchers.

## Difficulties differentiating dissociations

Kristof Kovacs, Kate C. Plaisted, and Nicholas J. Mackintosh  
*Department of Experimental Psychology, University of Cambridge, Cambridge CB2 3EB, United Kingdom.*

kk340@cam.ac.uk    kcp1000@cam.ac.uk  
njasm@bio.mole.cam.ac.uk    www.psychol.cam.ac.uk

**Abstract:** We welcome Blair's argument that the relationship between fluid cognition and other aspects of intelligence should be an important focus of research, but are less convinced by his arguments that fluid intelligence is dissociable from general intelligence. This is due to confusions between (a) crystallized skills and *g*, and (b) universal and differential constructs.

Blair's review provides a thorough account of how Gf<sup>1</sup> is grounded in fluid cognition (defined as the maintenance of information, inhibition and sustained attention), working memory and the prefrontal cortex. One of his aims is to establish that fluid cognition is dissociable from general intelligence, and that Gf can therefore be dissociated from *g*. Having established these dissociations, Blair then wants to encourage the development of tests of fluid cognition, or Gf, in children. Such tests would provide the potential to examine important questions, such as the relationship between fluid and crystallized intelligence in development. There is no question that investigations of fluid skills in typical and atypical development will provide valuable insights into both theoretical and applied issues in intelligence testing. However, it does not seem necessary to us to establish that fluid cognition can be dissociable from general intelligence in order to make this point.

Nor, indeed, does it seem to us that Blair has established in his review that fluid cognition is dissociable from general intelligence. In the five sections in which he reviews evidence for this apparent dissociation, it is quite clear that the evidence cited does no more than document a dissociation between fluid cognition and crystallized cognition (Gc). Essentially, all the studies that are said to show discrepancies between scores on different tests have used tests of fluid cognition and tests of crystallized intelligence. It comes as little surprise that Gf is dissociable from Gc: no one has disputed this. What is surprising is that Blair appears to consider Gc to be identical with *g* (see, e.g., sect. 3 of the target article). This impression is given, in part, by the slippage throughout this part of the review between the terms crystallized skills or intelligence and general intelligence or *g*; at one moment, he asserts that such and such evidence shows that Gf and Gc are dissociable; in the next sentence or paragraph, this evidence is said to show that Gf is dissociable from *g*.

This latter dissociation is not helped by Blair's attempt to argue for a residual Gf, an argument that would be disputed by Gustafsson (1984; 1988), who has claimed that Gf and *g* are essentially identical. Carroll (2003), a firm believer in *g*, has established that hierarchical factor analysis of a large test battery will show both a general factor *g* as well as a number of orthogonal factors, namely, Gf, Gc, Gv, etc. It is notable that, in two separate data sets, this residual Gf was either the smallest or second smallest factor, accounting for no more than a quarter of the variance accounted for by residual Gc. So, residual Gf is not very important – and, if these residual factors are orthogonal, one will not explain any of the variation in another.

But the slippage between terms introduces another flaw. Blair uses the term "general intelligence" as a synonym for "*g*" or "the *g* factor" throughout his article, and regularly substitutes "Gf" with "fluid cognition." This is unfortunate and misleading. General intelligence and fluid cognition are universal constructs that provide causal explanations of universal processes, and thus can be applied to a single individual; *g* and Gf, on the other hand, are differential constructs, being latent variables that are used in causal explanations of individual differences. To see the importance of this distinction, consider the main topic of the article: dissociation. In cognitive psychology, dissociation between A and B is assumed when (a) in experimental conditions, A does not interfere with B (or vice versa), or (b) in clinical studies, the injury of one part of the brain results in the malfunctioning of A while B remains intact (or vice versa). However, a

dissociation of two processes in this sense tells us nothing about the correlation between them. For example, measures of the strength of people's left hand will most probably correlate with those of the right hand, and this is not affected by the fact that (a) people can do things with their hands in parallel or (b) that people can lose their arms separately in accidents. Let us assume that a measure of the strength of the right hand shows a very high correlation with measures of the strength of the left hand. It is right to conclude that they measure the same *thing*, if by a "thing" we mean a latent causal variable that explains the covariation – in this case, perhaps general muscular makeup. But it would be foolish to conclude that they measure the same *thing* in the universal sense, since it would mean that we are born with only one hand. But we are born with two, and we can lose them one by one. In short, they can be dissociated, independently of the correlation.

The architecture of cognition does not determine the structure of correlations between performance on various tasks, and the latent variable structure of between-subject differences does not determine the architecture of cognition. Hence, the correlation matrix, or the factor (latent variable) structure of different tasks, tells us nothing about whether they can be dissociated in the cognitive psychologist's sense, or vice versa.

This leads back to the difference between the theoretical status of variables like *g* and *Gf*, or general intelligence and fluid cognition. Fluid cognition and general intelligence are universal constructs that give causal explanations at the level of the individual, whereas *g* and *Gf* are differential constructs that account for the common variance between various tests or tasks. Nevertheless, to be able to choose between different factorial solutions, differential constructs (such as *Gf*) must be grounded in universal ones (such as fluid cognition). But the methodological differences and the different scope of explanation must be kept in mind. If we pay attention to the difference between the (universal) constructs of general intelligence and fluid cognition, on the one hand, and the (differential) constructs of *g* and *Gf*, on the other, we will be in a better position to consider whether any of the two pairs can be dissociated.

NOTE

1. We prefer to use the "Gf" abbreviation used by Cattell and Horn to signify fluid intelligence; Blair's use of "gF" is unusual.

## Fluid intelligence as cognitive decoupling

Keith E. Stanovich

Department of Human Development and Applied Psychology, University of Toronto, Toronto, Ontario M5S 1V6, Canada

kstanovich@oise.utoronto.ca

<http://tortoise.oise.utoronto.ca/~kstanovich/index.html>

**Abstract:** The dissociation of fluid cognitive functions from *g* is implicit in the Cattell-Horn-Carroll gF-gC theory. Nevertheless, Blair is right that fluid functions are extremely important. I suggest that the key mental operation assessed by measures of gF is the ability to sustain mental simulation while keeping the relevant representations decoupled from the actual world – an ability that underlies all hypothetical thinking.

Blair displays immense scholarship in marshalling a broad array of evidence in neurobiology, psychometrics, and developmental science relevant to understanding the role of fluid cognition in cognitive theory. His main thesis appears early in the target article: "[D]issociation of fluid cognitive functions from other indicators of mental abilities through which *g* is manifest suggests that some reconceptualization of human cognitive competence is needed and may indicate instances in which *g* has reached or exceeded the limits of its explanatory power" (sect. 1.1, para. 3). Although I largely agree with this thesis, I think that

most of the work driving the field toward it has already been done in the form of the modern synthesis of intelligence research represented by the Cattell-Horn-Carroll (CHC) gF-gC theory (Carroll 1993; Cattell 1963; 1998; Geary 2005; Horn & Cattell 1967; Horn & Noll 1997; McGrew & Woodcock 2001).

The reason I make this somewhat deflationary comment is that many of the dissociations Blair discusses are easily handled by invoking the CHC theory. In many of the examples discussed in the target article, fluid intelligence dissociates somewhat from general intelligence because the latter is estimated from an amalgam of gF and gC tasks, and the particular effect discussed has differential impact on gF and gC. The result will be gF somewhat dissociated from *g* (but not as much as it dissociates from gC). This is certainly the case when we examine the secular rise in IQ known as the Flynn effect. Measured in standard units, the rise in gF is larger than the rise in *g* because general IQ measures contain components of crystallized intelligence which has not risen at all. Fluid intelligence dissociates from *g* in the Flynn effect because the secular rise is differential across gF and gC.

It is likewise with Duncan's demonstrations of the effects of damage to the dorsolateral prefrontal cortex (Duncan et al. 1995; 1996). One could say that these demonstrate that gF dissociates from *g*, but it is more parsimonious to simply say that the Duncan demonstrations show what CHC theory predicts: that, in certain cognitive domains, gF will dissociate from gC.

Nevertheless, I am in complete agreement with Blair that fluid functions are extremely important and that they are environmentally sensitive. I believe that research is homing in on the critical underlying operation(s) that makes fluid intelligence so critical to mental life. I have argued (Stanovich 2004) that the mental operation is one that accounts for a uniquely human aspect of our cognition – the ability to sustain an internal cognitive critique via metarepresentation. That extremely important mental operation is the decoupling of cognitive representations.

Cognitive decoupling supports one of our most important mental tasks: hypothetical thinking. To reason hypothetically, a person must be able to represent a belief as separate from the world it is representing. Numerous cognitive scientists have discussed the mental ability to mark a belief as a hypothetical state of the world rather than a real one (e.g., Carruthers 2002; Cosmides & Tooby 2000; Dienes & Perner 1999; Evans & Over 2004; Jackendoff 1996; Leslie 1987; Nichols & Stich 2003). Decoupling skills prevent our representations of the real world from becoming confused with representations of imaginary situations that we create on a temporary basis in order to predict the effects of future actions or to think about causal models of the world that are different from those we currently hold. Decoupling skills vary in their recursiveness and complexity. At a certain level of development, decoupling becomes used for so-called metarepresentation – thinking about thinking itself. Metarepresentation is what enables the self-critical stances that are a unique aspect of human cognition (Dennett 1984; 1996; Povinelli & Giambrone 2001; Sperber 2000; Stanovich 2004; Tomasello 1999). We form beliefs about how well we are forming beliefs, just as we have desires about our desires and possess the ability to desire to desire differently.

Sustaining cognitive decoupling is effortful, and the ability to run mental simulations while keeping the relevant representations decoupled is likely one aspect of the brain's computational power that is being assessed by measures of gF. Evidence that the key operation underlying gF is the ability to maintain decoupling among representations while carrying out mental simulation derives from work on executive function (e.g., Baddeley et al. 2001; Gray et al. 2003; Salthouse et al. 2003) and working memory (Colom et al. 2004; Conway et al. 2003; Kane & Engle 2003). First, there is a startling degree of overlap in individual differences on working memory tasks and individual differences in measures of fluid intelligence. Secondly, it is becoming clear that working memory tasks are only

incidentally about memory. Or, as Engle (2002) puts it, “WM capacity is not directly about memory – it is about using attention to maintain or suppress information” (p. 20). Engle (2002) goes on to review evidence indicating that working memory tasks really tap the preservation of internal representations in the presence of distraction or, as I have termed it – the ability to decouple a representation and manipulate it. What has for years been called in the literature generic cognitive capacity is probably the computational expense of maintaining decoupling in the presence of potentially interfering stimuli (why we look at the ceiling sometimes while thinking hard in a noisy room). If this is indeed the critical gF operation, Blair is correct that it is extremely important, because it is the basis of all hypothetical thinking.

## Fluidity, adaptivity, and self-organization

Elpida S. Tzafestas

*Institute of Communication and Computer Systems, National Technical University of Athens, Athens 15773, Greece.*

**Brensham@Softlab.Ece.Ntua.Gr**

**<http://www.Softlab.Ece.Ntua.Gr/~Brensham>**

**Abstract:** I propose a neuroscience and animat research-inspired model and a thought experiment to test the hypothesis of a developmental relation between fluid and crystallized intelligence. I propose that crystallized intelligence is the result of well-defined activities and structures, whereas fluid intelligence is the physiological catalytic adaptation mechanism responsible for coordinating and regulating the crystallized structures. We can design experiments to reproduce exemplified normal and anomalous phenomena, especially disorders, and study possible cognitive treatments.

The target article puts forth the hypothesis of a developmental relation between fluid and crystallized intelligence. I propose a model and a thought experiment to test this hypothesis. More specifically, I start from the biological assumption that the substrate of intelligence is a network of interconnected cells able to self-organize in response to external events, as well as due to endogenous dynamics. The biological properties of such networks may be summarized as follows: (1) individual cells are able to self-regulate in their local environment and in relation with neighbor cells, (2) individual self-regulation leads through self-organization to stable structures or cell clusters responsible for various functions, and (3) emergent cellular structures generally overlap, so that interactions between the emergent functions are partly unpredictable (Edelman 2004).

Within this configuration, the crystallized part of intelligence is the (static) result of the cellular structure’s activity, while the fluid part of intelligence is the physiological potential for self-organization and network restructuring. In this sense, crystallized intelligence appears behaviorally well defined and thus “measurable,” whereas fluid intelligence remains behaviorally ill-defined and not measurable alone, but only in relation with crystallized intelligence. This is because crystallized intelligence as measured on a particular task is the result of a more or less distinguishable structure that responds to regular tasks, while fluid intelligence is structurally hidden in the network, responds to novel or mutated tasks, and is finally responsible for new crystallized structures.

Fluidity in the cellular-network context can be established only through continuous adaptivity, that is, through constant change under environmental influence. Constant change thus is both history driven (i.e., developmentally cumulative in time) and situationally driven (i.e., highly interactive within a particular context). I should stress that environmental influence is qualified as influence by the individual perceptually and selectively (Steels & Belpaeme 2005). Furthermore, because perceptual schemas may be idiosyncratic, some influence may be endogenously

generated and not provided by the environment (Varela et al. 1991). A number of additional issues on fluidity are also important to the mechanism. First, a necessary feature for physiological fluidity is that the mechanism is self-catalytic or that it acts upon itself, in the sense of changing itself upon every “change command” it issues to one of the structures it controls. This leads to cognitive aging, because future self-organization rates are always lower than the present ones, although the reason or the mechanism for this being so is not well understood. Secondly, such physiological or self-organizational fluidity is usually regarded as being goal directed. However, because nothing forces emergent structures or even individual cells to take just external inputs, it is safe to assume that some goals will be self-generated or plainly endogenous within the individual, which leads us to usual idiosyncratic selective networks, a well-known structure possessing self-organization capabilities. Finally, the role of emotion, although obviously important, is not clear yet. We assume that emotion acts as a channel of social influence, which has therefore the double potential to speed up learning or drive an individual mad. By design then, fluid intelligence uses three types of information: (1) idiosyncratic information as explained before, which alone yields autonomic responses; (2) social information that triggers and interacts with emotional responses; and (3) crystallized information that contributes cognitive responses or cognitive parameters to complex responses. Normally, all three types are coordinated and reach a balance through self-organization that allows for coherent manifest behavior. Dysfunctions in any part are however possible, in which case all kinds of anomalies may emerge.

Within the described structural setting, normal phenomena such as those described in the target article may be reproduced (Balkenius 2000; Burgess et al. 2001): continuous favoring of one activity by the physiological fluid mechanism corresponds to focused attention, selection of activity C each time activity A or activity B could be invoked corresponds to abstraction, abrupt switches from activity to activity could be attributed to external stress (i.e., to abrupt changes to environmental conditions), and so on. Deviations or anomalies are also possible under certain conditions: (1) Innate learning impairments (e.g., exclusion from a particular perceptual subspace) or persistent external manipulation (e.g., bombardment with particular stimuli) may lead to destabilization of the usual structures and stabilization of new, unusual ones, thus inducing marginal or deviant behavior. In extreme cases, this may also lead to culturally driven alienation of generations (as in the case of families being raised in prisons and other marginal social environments). (2) Extreme endogenous network dynamics may lead to cognitive disorders without biological lesions being necessarily involved. For example, extremely slow self-catalytic rates may produce behavior perceived as retarded, while extremely low responses to visual emotional cues may act as a predisposition to autism. In all of these cases, self-organization will lead anyway to stable structures, natural albeit unusual (but not abnormal). However, fluidity itself allows for some limited remedy for such cognitive deficits, because stabilized structures cannot utterly change but may be a bit perturbed: for example, dyslexic people may read with conscious effort, and autistic patients may follow a gaze with conscious effort.

We can therefore design experiments to (1) produce self-organization and emergent structures with the aforementioned model, (2) allow the study of extreme cases in limited conditions of the system parameters, (3) perform perturbation studies to identify the degree and range of resistance of emergent structures to external stress, and (4) produce behavioral anomalies either because the external stress is very high (typical brains in atypical environments, according to Blair) or because the endogenous dynamics are such that the lowest external stress level or even a complete absence of stress induces phenomena such as activity loops or activity isolation (atypical brains in typical environments, according to Blair). The interplay between external social stress and endogenous

factors is especially interesting and important to study because all social disorders may be thought of and studied as emotional disorders and as resulting from repeated broad changes (Nesse 1998). Finally, we can design experiments that will prompt proper cognitive treatments for such cognitive disorders, for example, enriching the environment with controlled stimuli in the case of simulated autism, so as to hinder isolation.

### Mechanisms of fluid cognition: Relational integration and inhibition

Indre V. Viskontas and Keith J. Holyoak

Department of Psychology, University of California, Los Angeles, CA, 90095-1563.

indre@ucla.edu      holyoak@psych.ucla.edu

**Abstract:** Blair argues that fluid cognition is dissociable from general intelligence. We suggest that a more complete understanding of this dissociation requires development of specific process models of the mechanisms underlying fluid cognition. Recent evidence indicates that relational integration and inhibitory control, both dependent on prefrontal cortex, are key component processes in tasks that require fluid cognition.

As Blair notes, numerous studies have shown that fluid cognitive processes can be dissociated from general intelligence in individuals with prefrontal cortex (PFC) damage (Duncan et al. 1995; Waltz et al. 1999). Furthermore, Blair also presents evidence supporting the hypothesis that the development of fluid intelligence precedes and even “paves the way for the development of crystallized intelligence” (sect. 4.1, para. 1) (Cattell 1971; Horn & Cattell 1967). Others have observed that prefrontal cortex, which appears to be critical to fluid intelligence, plays a major role in cognitive development. For example, Damasio (1985) concluded that, “It seems probable that bilateral damage to the frontal lobes in infancy or childhood produces a more devastating effect on personality and cognitive ability than the same amount of damage sustained elsewhere in the brain at any time in the course of development” (p. 351).

The conceptual separation of fluid cognition from general intelligence sets the stage for more specific hypotheses concerning the processing mechanisms that support fluid cognition. Recent work on human reasoning supports the proposal that tasks requiring fluid cognition depend on specific functions of prefrontal cortex: the representation and manipulation of explicit representations of relations, and the capacity to inhibit responses based on salient but less complex representations (Robin & Holyoak 1995). In the target article, Blair cites a study by Waltz et al. (1999) in which we observed a decline in relational processing with frontal impairment. Specifically, patients with frontal-variant Frontotemporal Lobar Degeneration (FTLD) were able to solve problems that required processing a single relation at a time (e.g., understanding a simple relation such as “Mary is taller than Sally”); however, their performance fell to chance on problems that required integrating multiple relations (e.g., using the premises “Mary is taller than Sally” and “Alice is taller than Mary” to infer by transitivity that Alice is taller Sally).

Similar but less dramatic impairment of relational integration has been observed in Alzheimer’s patients who display frontal signs (Waltz et al. 2004). Our lab has also found (Morrison et al. 2004) that patients with frontal-variant FTLD are severely impaired in solving even 1-relation verbal analogies when active inhibition of a semantically related distractor is required (e.g., PLAY:GAME::GIVE:?, where the analogical answer PARTY competes with the semantically-related distractor TAKE). Solving the kinds of problems associated with fluid cognition thus requires both relational integration (a core function of working memory) and inhibitory control.

We have recently extended these findings by investigating relational integration and inhibitory control in younger, middle-aged, and older adults (Viskontas et al. 2004; in press). A general decline in working memory capacity with age is well documented ( Craik et al. 1990; Dobbs & Rule 1989). Most of the evidence indicates that while primary or immediate memory capabilities, such as digit span, remain relatively constant throughout life, working memory processes that involve the actions of the central executive, such as manipulating information held in memory, are vulnerable to age (Craik et al. 1990). In our reasoning tasks (including transitive inference, and versions of Raven’s Matrices problems), participants had access to all of the information needed to make inferences at all times; we thus minimized demand on short-term storage systems. However, we varied the number of relations that had to be manipulated to find a solution; as more relations had to be integrated, the central executive would be increasingly taxed. In addition, we varied whether or not a superficially similar distractor item was present to compete with the correct relational response.

We found that, as people age, their ability to manipulate multiple relations declined. Moreover, the number of relevant relations interacted with the requirements for inhibitory control, such that older people were most vulnerable when high levels of relational complexity were coupled with high need for inhibition of superficially related alternatives (see Fig. 1).

Our results indicated that this apparent decline in processing capacity in working memory follows a gradual pattern: younger adults reached their working memory capacity when integrating four relations, middle-aged people had some trouble integrating three relations, and older adults had trouble integrating even two relations. This pattern of results suggests that aging does not produce a catastrophic failure in processing multiple relations, as was observed for patients with extensive frontal lobe degeneration (Waltz et al. 1999). Rather, the decline in relational

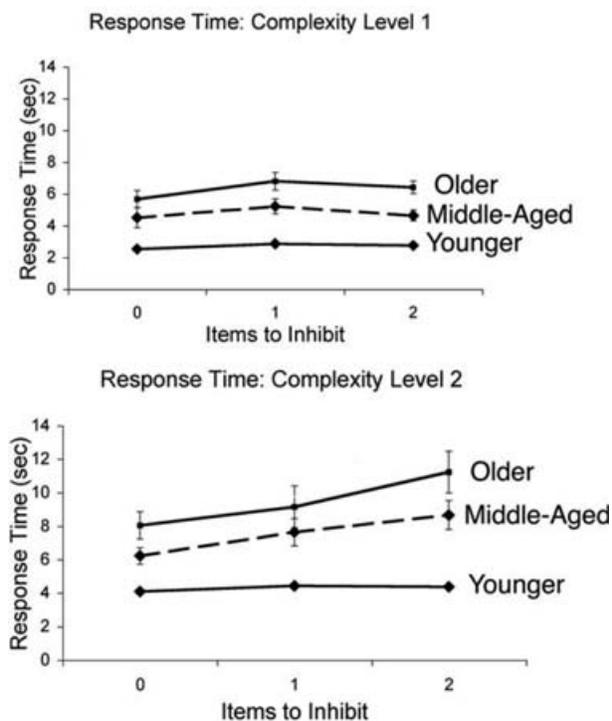


Figure 1 (Viskontas & Holyoak). Response time in the People Pieces Analogy task for three levels of inhibition at the first two levels of complexity for younger ( $n = 31$ ), middle-aged ( $n = 36$ ), and older ( $n = 22$ ) groups (error bars depict standard error of the mean). Data from Viskontas et al. (2004).

integration follows the trajectory of the development of relational integration in reverse (Halford 1993; Richland et al. 2004). Even when memory-storage demands are minimized by the continual presence of the premises, normal aging is accompanied by declines in processing capacity that cause impairments in relational integration and inhibitory control.

We have developed a computational model of relational reasoning that has been used to simulate differences in reasoning ability attributable to changes in the neural mechanisms responsible for relational integration and inhibitory control (Hummel & Holyoak 2003; Morrison et al. 2004; Viskontas et al. 2004). By defining the processes underlying fluid cognition in specific computational terms, it should be possible to make predictions concerning which measures of general intelligence will bring age-related deficits to light, and which will fail to show any decline. We can also apply this deconstructive method to daily tasks faced by the general population. This approach may prove fruitful in assessing individual differences in cognition within large populations.

## Phlogiston, fluid intelligence, and the Lynn–Flynn effect

Martin Voracek

*School of Psychology, University of Vienna, A-1010 Vienna, Austria.*

[martin.voracek@univie.ac.at](mailto:martin.voracek@univie.ac.at)

<http://mailbox.univie.ac.at/martin.voracek/>

**Abstract:** Blair's assertion that fluid intelligence ( $gF$ ) is distinct from general intelligence ( $g$ ) is contradictory to cumulative evidence from intelligence research, including extant and novel evidence about generational IQ gains (Lynn–Flynn effect). Because of the near unity of  $gF$  and  $g$ , his hypothetical concept of  $gF'$  ( $gF$  "purged" of  $g$  variance) may well be a phlogiston theory.

In 1669, the German chemist and adventurer J. J. Becher advanced an entirely nonsensical, but regrettably influential, hypothesis regarding the nature of combustion that became later to be known as phlogiston theory. According to Becher and his followers, phlogiston – some kind of "elastic principle," without color, odor, taste, or weight – is present in all flammable ("phlogisticated") materials. During combustion ("dephlogistication"), this hypothetical matter was thought to be given off. Phlogiston theory was strongly supported throughout most of the eighteenth century, until the French chemist A. L. Lavoisier, now rightly recognized as the father of modern chemistry, discovered the true nature of combustion (namely, the role of oxygen therein, along with the law of conservation of mass). I confess that several key points in Blair's target article sound phlogiston-like to me.

Blair considers the relation of fluid intelligence ( $gF$ ; his term is "fluid cognitive functioning") to general intelligence ( $g$ ), asserting that  $gF$  is distinct from  $g$ . This is in stark contrast to the cumulative empirical record from intelligence research. There is now broad consensus that the loading of  $gF$  on the highest-order factor ( $g$ ) is essentially unity; that is, that the two are effectively identical (Carroll 1993; Gustafsson 1984). Although some debate about this view appears to be still going on (Carroll 2003; Johnson & Bouchard 2005), even impressively cautious and critical commentators like Mackintosh (1998, pp. 227, 297) agree with the consensus view about this aspect of the hierarchical structure of human intelligence.

As a consequence of the near unity of  $gF$  and  $g$ , there appears to be no room left for Blair's hypothetical concept of  $gF'$  (i.e.,  $gF$  "purged" of  $g$  variance, to be studied independently from  $g$ ). Importantly, Blair's outline of  $gF'$  lacks any data-analytic examples. Should these be undertaken, I anticipate that it will be recognized that  $gF'$  consists merely of a hodgepodge of

method variance, measurement error, and, possibly so, residues of visuospatial ability facets ( $gV$ ) contaminating our best vehicle of  $gF$  (i.e., Raven-type matrices tests of abstract reasoning).

Blair sets out various lines of evidence allegedly supportive for his assertion of a  $gF$ – $g$  dissociation. Among others, the so-called Lynn–Flynn effect (for the name, see Rushton [1999, p. 382]; for reviews, see Neisser [1998] and Fernández-Ballesteros et al. [2001]) – that is, the secular increase in IQ and related measures of achievement – is also called on. Specifically, Blair asserts that there is evidence for a  $gF$ – $g$  dissociation in regard to the rising mean IQ of populations over time (target article, sect. 3.1). According to Blair, IQ gains have almost entirely occurred on measures of  $gF$  and not on measures of crystallized intelligence ( $gC$ ).

A more principal objection is waived here: it is perhaps not the best idea to try to prove or support one highly debatable matter (i.e., a supposed  $gF$ – $g$  dissociation, along with the meaningfulness of the  $gF'$  concept) with another matter that is itself far from being well understood (i.e., the Lynn–Flynn effect). Rather, the focus will be on Blair's claim regarding the Lynn–Flynn effect. I opine that his presentation is based on an incomplete narrative review of the pertinent literature, with selective referencing. Elsewhere (Blair et al. 2005a), he has argued that educational changes have largely been responsible for the Lynn–Flynn effect. This stance appears to be lopsided, overlooking the fact that generational IQ gains have been ascertained even in preschoolers, which makes nutritional factors a very likely explanation (Colom et al. 2005; Lynn 1990). Further, this stance discounts the real eventuality that the IQ gains are not necessarily solely environmental, but rather are also compatible with demographic (i.e., genetically based phenotypic) changes over time (Mingroni 2004).

The international pattern regarding the Lynn–Flynn effect is erratic: the highest IQ gains have been observed in the Netherlands and further in France, Japan, and Israel (Flynn 1987; 1998b), whereas below-average gains have been reported for countries such as Great Britain, Ireland, New Zealand, and Australia (Flynn 1987). IQ gains may have already ceased or even reversed in Norway and Sweden (Flynn 1998a; Sundet et al. 2004) and actually have recently reversed in Denmark (Teasdale & Owen, in press). Similarly, there are enigmatic cross-national differences in the  $gF$ : $gC$  gain ratios: whereas  $gF$  gains have been larger than  $gC$  gains within the Anglo-American sphere, there have been noticeable gains on vocabulary tests ( $gC$ ) in Germany and in the German-speaking countries Austria and Switzerland (Flynn 1987; 1998a; 1999; Schallberger 1987; Schubert & Berlach 1982), approaching the gains seen there on  $gF$  measures.

Adding to this evidence, here I bring forward new data (Voracek 2002). Based on a sample of 5,445 consecutively referred psychiatric patients (Vienna, 1978–1994) and using Flynn's (1998b, p. 551) methodology, the estimated IQ (i.e., the amount of IQ change per decade; Jensen 1998, p. 319) on a  $gC$  measure (the multiple-choice vocabulary test MWT; Lehrl et al. 1995) was 1.98, whereas IQ was 2.47 on a  $gF$  measure (a 30-item Rasch-scaled version of Raven's Standard Progressive Matrices; Wytek et al. 1984). It is not only intriguing to see that the Lynn–Flynn effect appears to generalize to subpopulations such as psychiatric patients, too, but also that – contrary to Blair's general claim – there certainly is no "dissociation" of  $gC$  and  $gF$  gains in this study (the  $gC$ : $gF$  gain ratio being a modest 1:1.25).

Further, a novel research approach was pursued in the same work (Voracek 2002): I wondered whether a Lynn–Flynn effect could be ascertained from mean group scores on the widely used MWT, as incidentally reported in research from German-speaking countries, taking into account publication year. Of course, each mean MWT score from a small sample of research subjects is unrepresentative for the general population – but what would be the aggregate evidence, based on a great many of such samples? By means of a cited-reference

search strategy, I located 288 primary studies, published in 1973–2002, which reported mean MWT scores for 527 groups of German, Austrian, and Swiss study participants (healthy adults as well as patient samples), totaling nearly 29,000 subjects. This large-scale meta-analysis of unrepresentative samples yielded an  $\Delta IQ$  estimate of 2.61 for the gC measure MWT. This figure is comparable with the finding from the Austrian psychiatric patient sample and further nicely dovetails with extant evidence from population-based studies. Flynn (1984) originally arrived at a  $\Delta IQ$  estimate of about 3 (USA, 1932–1978), which was later updated to about 2.5 (USA, 1972–1995 [Flynn 1998c]). A reanalysis of the extant international evidence by Storfer (1990, p. 439) suggests that  $\Delta IQ$  was about 3.75 during the first quarter of the twentieth century, about 2.5 for the subsequent decades until about the mid-1960s, and probably less since then.

To summarize, Blair's claim of a gF–gC dissociation supposedly seen in the Lynn–Flynn effect (in order to support his gF' concept) is neither supported by the empirical record in this area nor by the new findings presented here. We are all well advised not to devote ourselves to phlogiston theories of human intelligence.

## How relevant are fluid cognition and general intelligence? A developmental neuroscientist's perspective on a new model

Marko Wilke

*Department of Pediatric Neurology and Developmental Medicine, Children's Hospital, University of Tübingen, 72076 Tübingen, Germany.*

Marko.Wilke@med.uni-tuebingen.de

**Abstract:** Blair boldly proposes a model integrating different aspects of intelligence. Its real-life value can be put to the test by using programs designed to develop children's abilities in areas predicted to be crucial for minimizing adverse outcome. Until support from such programs is available, the model is an interesting hypothesis, albeit with remarkable possible repercussions. As such, it seems worthy of further development.

In his target article, Blair provides a comprehensive model for identifying and describing different aspects of intelligence (broadly defined), including the neurobiological underpinnings. As with many models proposed, a developmental neuroscientist is tempted to ask: So what? Numerous models are out there, aiming to describe and explain the multitude of observations regarding "intelligence" both in impaired and unimpaired subjects. What makes this work stand out is the direct applicability of the concept and, even better, the fact that we are liable to put it to the test both clinically and in neuroscience research. Clinically, those working with children from disadvantaged backgrounds or with children showing mental retardation can direct their attention towards developing programs aiming to influence the specific aspects of fluid cognition that Blair hypothesizes to be central in determining later outcome, as measured by as yet inappropriate tests. For neuroscience research, a number of directions seem to suggest themselves as to how the pertained distinction of fluid and general intelligence could be disentangled, for example, by using modern neuroimaging methods. As it is, the target article describes a bold new concept, thoroughly doing away with the monolithic idea of *g*-and-nothing-else. As such, it is likely to draw criticism from "proponents of the old order," and probably rightly so. However, programs designed to test the concept can (and, hopefully, will) be developed that enable supporting the concept with not only theoretical neuroscience data (such as functional magnetic resonance imaging [fMRI]) but, ideally, with the very practical and highly important result of children simply doing better in life. If this were the case, Blair must be commended for boldly going down this road. If not, then it will be just another model, with not much relevance for clinicians' daily work.

There are drawbacks, of course. What about the role of the thalamus and the cerebellum, both of which have been considered cornerstones for the cognitive impairment seen not only in schizophrenia (Clinton & Meador-Woodruff 2004; Rapoport et al. 2000; Schultz & Andreasen 1999)? Considering that the thalamus was classically used to define prefrontal cortex as the projection area of the mediodorsal thalamic nucleus, should it not be expected to play some kind of role, as a gatekeeper or in some other form, hitherto unknown? In our study on gray matter correlations with a broad measure of intelligence, the thalamus was implicated in these correlations in a connectivity analysis, as was the medial temporal lobe (Wilke et al. 2003). Interestingly, the correlation of global gray matter and IQ (as assessed by the Wechsler batteries and thus reflecting mainly general intelligence) only develops during childhood, perhaps lending support to the notion of fluid skills playing a larger role in early childhood. Also, if there is a dissociation of fluid skills and general intelligence in adults in a way that only fluid skills are affected, should there not also be a model for an isolated decrease in general intelligence which could shed additional light on the issues? Finally, could the differential effects of prefrontal cortex lesions in the neonatal period and in adulthood not also be seen as simply being an indication of the generally larger cortical plasticity in children? I am sure others will come up with more, and more serious, issues this model has to accommodate, and this process will be interesting to follow.

Still, it also seems interesting to complement this work with two timely studies published recently. In one fMRI study, Breitenstein et al. (2005) distinguished good learners from bad learners by the amount of hippocampal activation. This is all the more interesting as all subjects were healthy adults, indicating that, employing the right kind of paradigm and using performance data as a guide, it may be possible even in healthy subjects to tease out the different aspects of cognition described by Blair. Even more interesting and lending strong support for one of the main theses of the target article is the study by Heinz et al. (2005). Here, subjects with three genetically defined variants of a serotonin-transporter system were investigated by using fMRI and applying the concept of functional connectivity. This serotonin transporter is believed to play a crucial role in a subject's liability to develop major depression. It could be demonstrated that the strength of the coupling between the amygdala and the ventromedial prefrontal cortex is a function of the genetic variant of the subject. Therefore, a genetic influence on behavior via the pathway that plays a crucial role in Blair's model of cognition-emotion reciprocity is suggested. This adds evidence for a genetic contribution to or modulation of the putative environmental influence that Blair hypothesizes, which (by virtue of lending support to the mechanism in itself) further strengthens the point made about this link.

Overall, I believe this to be a very interesting model which accommodates a number of observations and lends itself to rigorous testing. As it is, however, its virtues, beyond explaining the observed, can be assessed only in years to come, following extensive discussions of the pros and cons. It is as yet too early to decide, but for the sake of children possibly profiting from a more targeted approach to support, I wish the model well.

## Can fluid and general intelligence be differentiated in an older adult population?

Nancy A. Zook<sup>a</sup> and Deana B. Davalos<sup>b</sup>

<sup>a</sup>Department of Psychology, Purchase College, State University of New York, Purchase, NY 10577; <sup>b</sup>Department of Psychiatry, University of Colorado Health Sciences Center, Denver, CO 80262.

nancy.zook@purchase.edu Deana.Davalos@UCHSC.edu

**Abstract:** The question of whether fluid intelligence can be differentiated from general intelligence in older adults is addressed. Data indicate that the developmental pattern of performance on fluid tasks differs from the pattern of general intelligence. These results suggest that it is important to identify changes in fluid cognitive functions associated with frontal lobe decline, as they may be early indicators of cognitive decline.

It has been suggested that fluid intelligence and general intelligence can be differentiated both in terms of neurobiology and cognitive performance (Blair's target article; Duncan et al. 1995; Kane & Engle 2002). Although researchers show increasing interest in understanding the differences between types of intelligence, the practical implications of this potential dissociation has been poorly addressed. Blair focuses on child development and suggests that fluid intelligence, compared with general intelligence, may be affected by different developmental experiences and different cortical processes. Most importantly, Blair stresses that the assessment of fluid intelligence skills may provide us with unique insight into early mental development and how this relates to adaptive success in children from varying social and economic backgrounds.

The relationship between fluid intelligence and general intelligence is particularly compelling in both early childhood and late adulthood, given the neurobiological changes that take place during each period. Specifically, the late development of the prefrontal cortex (PFC) in children/adolescents and the relatively early atrophy of the PFC in late adulthood suggest that during these stages, unique dissociations between general intelligence and fluid intelligence may be the most robust (Leigland et al. 2004). We emphasize the role of the PFC, given that one of the first studies to detect the fluid intelligence-general intelligence dissociation focused on patients with PFC injuries (Duncan et al. 1995). In Duncan et al.'s (1995) research, patients with PFC injuries obtained above-average full-scale IQ (FSIQ) scores on the Wechsler Adult Intelligence Scale (WAIS) compared to the control group. However, when given a test of fluid intelligence, their performance was significantly below that of control participants. Similarly, Fry and Hale (1996) found fluid abilities to be specifically impaired in patients with frontal lobe damage, whereas crystallized abilities were intact. Kane and

Engle (2002) interpreted this dissociation as possibly reflecting the fact that standardized intelligence batteries average performances across subtests varying in their assessment of fluid intelligence versus crystallized intelligence, potentially diluting the effect of PFC insult on fluid intelligence. Blair and others have noted that findings from these clinical studies assessing frontal lobe damage are provocative, but only speculative due to the small sample sizes used.

Given these results, a relevant question to ask is whether this pattern is present in normal development. Could performance on fluid tasks in early development (when the PFC is immature) and late development (when the PFC is declining) show the differentiation seen in patients with damage to the prefrontal cortex, between general intelligence and performance on fluid/executive ability tasks? Recent work in our lab has found that across development, executive function performance seems to correspond to the development and decline of the PFC (see Fig. 1). This U-shaped pattern of executive ability/fluid scores across development contrasts studies assessing general intelligence which show that performance remains developmentally stable across the lifespan (Horn 1970).

Our data, along with those of others, suggest that the issues that Blair addresses in early development may also be relevant in late adulthood. This may be specifically true in determining whether fluid intelligence measures provide us with unique insight into cognitive decline associated with aging, and whether these measures are distinct from general intelligence measures in their ability to predict clinical outcome and success in everyday living. To assess the dissociation between frontal measures and psychometrically defined global measures previously noted in PFC patients, with a larger and more generalizable sample, we chose to focus on older adults. Increasing evidence indicates a decline in frontal lobe functioning with age (e.g., Braver & Barch 2002; Bunce 2003; Haug et al. 1983; Raz 1996; Raz et al. 1993). Isingrini and Vazou (1997) found that performance on frontal lobe tasks correlated with measures of fluid intelligence but not crystallized intelligence in a group of older adults. Schretlen et al. (2000) hypothesize that "age-related atrophic changes in frontal brain structures undermine the functioning of executive abilities, and this results in the gradual

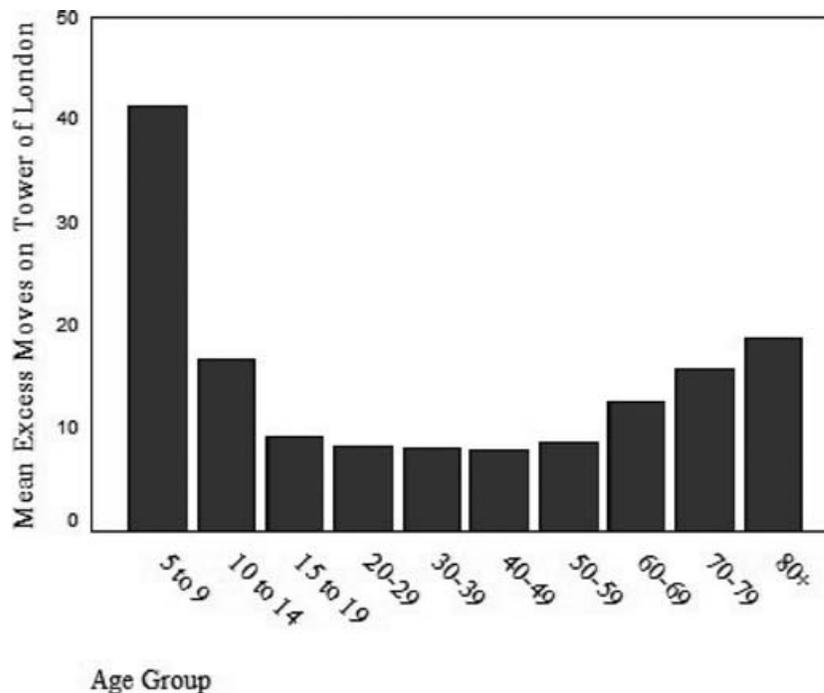


Figure 1 (Zook & Davalos). Performance on the Tower of London, an executive ability task, throughout the life span.

decline of fluid intelligence” (p. 53). Schretlen et al. found that age-related declines in executive ability and frontal lobe volume accounted for a significant amount of variance in fluid intelligence and revealed a significant negative correlation between fluid intelligence and age. Using various measures of intelligence, we have found converging evidence that indicates that, while crystallized intelligence remains stable, fluid intelligence and executive function performance decline with age, with the most prominent decline beginning in the 60s (Zook et al., in press). In another study looking specifically at older adults, we found that although full-scale intelligence scores in our sample of older adults were above the population mean of 100 and significantly higher than in the younger adult group, the older adults’ performance on a fluid intelligence task was significantly below that of the younger adults. Performance on two executive ability tasks, the Tower of London and the Wisconsin Card Sorting Task, were also significantly lower in the older adult group.

These results support Blair’s proposal that a neurobiological model is needed that differentiates cognitive processes associated with the PFC from a general, psychometrically defined general intelligence across the life span. It is important to understand the specific developmental aspects of fluid intelligence (e.g., late development and early decline of the PFC) not only as part of a theory of cognitive development, but also in terms of neuropsychological assessment and intervention. Following from the ideas presented by Duncan et al. (1995), Kane and Engle (2002), and our data, we suggest that intelligence batteries such as the WAIS and WISC may not identify specific types of impairments in cognitive functioning associated with fluid intelligence. Blair points out that it is important to study cognitive function and variations in performance by using a neuropsychological and psychometric framework and to look at development in typical as well as atypical populations. It is also suggested here that when studying and assessing cognitive function across the life span, multiple measures of fluid intelligence should be used in addition to more general measures of intelligence. Such an approach could identify functional cognitive differences and allow for the implementation of interventions both developmentally and in late adulthood.

## Author’s Response

### Toward a revised theory of general intelligence: Further examination of fluid cognitive abilities as unique aspects of human cognition

Clancy Blair

*Human Development and Family Studies, Pennsylvania State University,  
University Park, PA 16802-6504.*

cbb11@psu.edu

**Abstract:** Primary issues raised by the commentaries on the target article relate to (1) the need to differentiate distinct but overlapping aspects of fluid cognition, and (2) the implications that this differentiation may hold for conceptions of general intelligence. In response, I outline several issues facing researchers concerned with differentiation of human cognitive abilities and suggest that a revised and expanded theory of intelligence is needed to accommodate an increasingly diverse and varied empirical base.

## R1. Introduction

A number of important issues and challenges are raised by the commentaries on the target article, which need to be addressed. It is worth noting at the outset, however, that most of the commentaries are in agreement with the need to clearly differentiate fluid cognitive abilities from general intelligence. All but one or perhaps two of the commentaries take the position that there is something to be gained by such differentiation, and really none presents an all-out defense of *g*, the general factor of intelligence, in an attempt to discredit the target article’s primary thesis. This is of considerable interest and perhaps suggests that reliance on the explanatory power of the mathematically derived general factor in research on human intelligence is appropriately on the wane. Certainly the scientific foundation on which the general factor rests is very clear, and it is without question one of the most enduring constructs in the history of psychological research. However, the individual differences framework for the construct is inherently limited by its correlational nature and, despite its claims to comprehensiveness, has not been able to provide a well-grounded explanation for the aspects of human behavior with which it is associated. Accordingly, I suggest that the general factor in its familiar form is headed for the margins of scientific inquiry because of a fundamental lack of specificity. But whether the construct will go, in the immortal words of T. S. Elliot, “not with a bang but a whimper,” or whether Samuel Clemens’ “the report of my death was an exaggeration” will prove a more apt characterization of the future of the general factor as an aspect of research on intelligence, is certainly open to question.

Although one could argue endlessly about whether the construct of general intelligence in its familiar form will or will not fade from the scientific limelight, it is my opinion, and I think that of many others, that the decline of the explanatory power of the general factor has been apparent for some time. The relevant question is how to best fit new data and insight into the old order of *g*. This is really the core of scientific change in the sense of Thomas Kuhn (1962). How can we best go about instantiating change in the study of human cognitive abilities within the time-honored framework of *g*? In part, it is the variety of ways in which this may be accomplished that lies at the heart of the issues raised by the commentaries.

In this response, I examine some logical next steps in revising the theory of general intelligence to accommodate an expanded view of fluid cognition. In doing this, I first respond to commentary focusing on theory development and the expansion of the empirical base in research on intelligence. I then turn to what I think are some of the key issues facing researchers concerned with the differentiation of fluid cognitive abilities from general intelligence. Here I examine definitional issues and address concerns regarding the unity versus diversity of executive function (EF), working memory (WM), and fluid intelligence (gF). In response to commentators suggesting the need for greater differentiation of EF, WM, and gF, I outline evidence in support of an integrated fluid cognitive construct. In this, I also examine the role of attention in fluid cognitive functioning and juxtapose the model presented in the target article with John Duncan’s

adaptive-coding model of gF. I also further examine the role of emotion and the stress response in fluid cognition and conclude by suggesting that research on intelligence can best advance through the examination of associations among psychological and neurobiological variables.

## **R2. Revising the theory of general intelligence**

Interest in the way forward in the study of human cognitive abilities is the specific focus of the commentaries by **Anderson, Flynn, Ford, and Wilke**. The commentary by Flynn, in particular, thoughtfully articulates the need for a revised theory of intelligence. The research base on the study of intelligence now indicates that the current individual-differences frame must be expanded to accord equal weight to neurobiological and sociological influences on the structure of human cognitive abilities. I believe such a revision to be imperative if research on intelligence is to move forward.

Without a revised theory of intelligence, our understanding of human cognitive abilities is inherently one-dimensional. It is necessary to “transcend g,” to use **Flynn’s** phrase, in order to adequately characterize the complex nature of relations among cognitive abilities. Within the current individual-differences framework of the general factor, correlation among abilities is expected. But this correlation structure represents only one view of relations among cognitive abilities. Neurobiological and sociological data provide different views, particularly for fluid cognitive skills. Like a holographic image when tilted at an angle or the reflection in a fun-house mirror as the carnival-goer moves from side to side, the one-dimensional individual-differences structure of the general factor comes apart when examined in light of historical and neuropsychological data. The approach outlined by **Flynn** of a three-dimensional general factor-architectonic-sociological model begins to provide the necessary frame within which to array the increasingly varied and complex findings of intelligence research. Such a model will ultimately reconcile diverse and seemingly contradictory findings in the study of intelligence. These include, among others, findings from historical data on long-term trends in cognitive abilities and from developmental neuroscience examinations of the structure of human cognitive abilities. Although it is beyond the scope of this response to develop this model further, it is hoped that **Flynn’s** call for a symposium on the future of intelligence research will be heeded and will array the requisite expertise needed for the advancement of theory in the study of intelligence.

Developing and refining a multidimensional model of intelligence is a very high priority given the long-standing and influential profile of the general factor. As noted by **Ford**, understanding aspects of cognition that may be more amenable to environmental influence has been and remains a high priority for researchers studying the effects of early experience and early intervention for children facing psychosocial or biological adversity. A revised and expanded model of intelligence that incorporates multiple levels of influence can provide some explicit indications of how and in what ways early experience may have its effects. Furthermore, as noted by **Ford**, longitudinal studies of early, highly structured experiential

interventions to influence the developmental course of intelligence, particularly those using randomized designs, present an unparalleled data source for ongoing examination and revision of a multidimensional model of intelligence.

Of course, as **Anderson** makes clear in his commentary, the study of development can be seen as a unique source of variance in intelligence, one that is distinct from individual differences associated with the general factor. I agree to some extent with **Anderson’s** approach but feel that it may make too sharp a distinction. In contrast to **Anderson**, I believe it is necessary to fully incorporate neurobiological factors, as well as sociological factors, when considering development in context. For my own part, I also find the role of emotion and stress in cognition to be considerably underdeveloped and an area of research likely to yield valuable information regarding influences on cognitive development, particularly for children facing early psychosocial adversity.

As noted by **Wilke**, the model presented in the target article suggests new directions for research that, if fruitful, will be of both basic and applied science value. **Wilke** describes two examples of the types of neuroscience research that might begin to provide evidence relevant to the model. He also raises important questions regarding the relation of the model to various brain structures. Almost certainly, a more comprehensive neural network approach that incorporates relations among multiple brain areas will be needed to characterize complex excitatory and inhibitory activations associated with fluid cognitive processes and their relation to other cognitive abilities. Advances in the study of cognitive aging, particularly the study of frontal-parietal connectivity in memory decline in typical aging and dementia (**Buckner & Wheeler 2001; Hedden & Gabrieli 2004**), clinical neuropsychological work on the role of specific areas of frontal cortex in memory deficits (**Stuss & Alexander 2005**), findings from training studies of working memory (**Olesen et al. 2004**), and findings regarding the role of frontal-striatal connectivity in self-regulation and cognitive control (**Mink 2003**), provide examples of the ways in which interrelations among multiple brain areas influence human cognition. It is hoped that the developmental neuroscience perspective on fluid cognitive abilities provided by the target article will ultimately inform and be informed by continued work of this type.

## **R3. WM, EF, and gF: How similar, how different?**

For theory development in the study of human cognition to move forward, it is necessary to come to some consensus regarding terms and constructs. To my mind, what is perhaps the most pointed critique of the target article concerns the idea that I did not differentiate thoroughly enough among gF, WM, and EF; that I overemphasized similarity among them and downplayed the distinctiveness of each. Several commentators (**Benga, Birney, Bowman, & Pallier [Birney et al.]**; **Burgess, Braver, & Gray [Burgess et al.]**; and **Heitz, Redick, Hambrick, Kane, Conway, & Engle [Heitz et al.]**) suggest that by focusing on fluid cognition more generally rather than on distinct cognitive abilities, key issues in the study of human cognition were overlooked. To set the stage for the discussion that

follows, it is important to note that I chose a somewhat broad level of resolution when characterizing fluid cognitive abilities in order to highlight the extent to which overlapping processes of working memory, attention shifting, and inhibitory control are distinct from more automatized and crystallized aspects of cognition. It was not my intention for readers to come away with the impression that I believe fluid cognition to be a unitary construct, isomorphic with *gF*, and dependent exclusively upon the prefrontal cortex. In fact, I was fairly explicit on the differentiation of distinct aspects of fluid cognition and the role of diverse brain regions in fluid abilities (see sect. 2.1). I think my central point – that fluid aspects of cognition have been taken in many instances to be highly similar, if not identical to general intelligence, but somewhat paradoxically have shown patterns of change across individuals and historical cohorts that clearly dissociate them from general intelligence – is one well worth making. But it is made within a shifting definitional sea. What is referred to as working memory by Kyllonen and Christal (1990) would seem to map only imperfectly onto working memory as defined by Baddeley (1986) or executive attention as defined by Posner and Rothbart (2000).

In part, but only in part, definitional issues in the study of fluid cognitive abilities result from the fact that researchers use different terms to describe constructs that are highly similar. Sorting out the similarity from the difference in these terms is no small task. For my own view, as well as that of others (Miyake et al. 2000), WM is a distinct component of an overarching EF construct that also contains inhibitory control and attention-shifting functions. Several of the commentaries provide some valuable analyses examining these different aspects of fluid cognitive abilities. In the data of **Burgess et al.**, **Demetriou, Viskontas & Holyoak**, and **Zook & Davalos** and the critiques by **Benga, Birney et al.**, and **Heitz et al.**, readers are provided with very thoughtful analyses of relations among constructs. However, several commentators confidently proclaim *gF*, WM, and EF to be distinct, an idea that no doubt has some validity, but one that available evidence does not clearly support.

#### **R4. The potent combination: Working memory and inhibitory control**

**Burgess et al.** provide an illuminating example that builds upon the analysis supplied by Gray et al. (2003) to indicate that both *gF* and WM span are related to a specific pattern of brain activity associated with *n*-back working memory trials that contain a strong interference component (lure trials). That *gF* and WM span show similar relations to brain activity associated with lure trials in an *n*-back working memory task, more so than with target and low-interference trials, is highly consistent with the presumed overlap of WM and *gF*. It does little, however, to differentiate the distinction between these two constructs. It does perhaps help in some ways to differentiate the various components of EF, although the inclusion of a trial type of high interference but low working memory demand would be helpful in making inference here. Had such a trial type been included, the results would likely continue to provide support for the idea that it is the combination of high working memory demand with the need to inhibit

interference that is a central aspect of cognitive competence.

The analysis by **Burgess et al.** suggests that the maintenance of information in working memory and the inhibitory control aspects of EF are distinguishable but when combined present a highly meaningful pattern of brain activation. Similarly, the analysis by **Heitz et al.** indicates that inhibitory control ability as measured by a flanker task reliably distinguishes individuals with high WM span from those with low WM span. In both instances, the authors' findings indicate that the executive functions of working memory and inhibitory control are combined within persons into something like a "unitary" fluid cognitive construct. As outlined in the target article, various sources of evidence indicate that in combination these aspects of cognition possess a powerful relation to real-world ability – one that is distinguishable from *g* and essentially embodied in constructs such as working memory capacity (Engle 2002) and executive attention (Posner & Rothbart 2000) and well represented in Diamond's (2002) work on EF in early childhood.

The role of working memory/inhibitory control in cognitive competence (without an underlying concern to differentiate the constructs) is also clearly presented and shown to apply across the life span in the insightful analyses by **Viskontas & Holyoak** and **Zook & Davalos**. Both of these commentaries provide highly useful data indicating the applicability of a fluid cognitive approach to the study of cognitive aging. Viskontas & Holyoak introduce the construct of relational complexity, a construct denoting high working memory demand but also perhaps something more, and present data to indicate that tasks that combine relational complexity with inhibitory control are particularly difficult for older adults. Furthermore, operationalization of inhibitory control in the analysis by Viskontas & Holyoak through the use of superficially related semantic items that interfere with relational processing is similar to the use of lure trials to generate interference in the analysis by **Burgess et al.** In this way, Viskontas & Holyoak's analysis provides further evidence for a convergence of data on the combined executive functions of working memory and inhibitory control as central aspects of cognitive competence.

**Viskontas & Holyoak** also provide some indication that individuals with disruption of a frontal-temporal cortical network have difficulty with even simple relational complexity when presented with a verbal analogy with a semantically related distractor. Here, the use of verbal analogies may be an important feature of the design. It would be valuable to know whether similar results are obtained with numerical or spatial stimuli. If so, these data suggest, as with the analysis by **Burgess et al.**, that the potency of the interference effect is inversely related to WM function. Of further interest in Viskontas & Holyoak's analysis is the extent to which relational complexity, although seemingly a manifestation of working memory ability, may be dependent on processes beyond the EF of working memory that might be aspects of *gF* or *g*, such as abstraction ability or decoupling abilities described by **Garlick & Sejnowski** and **Stanovich** (discussed in sect. R8).

Similar to the effect of chronological age on the combined working memory/inhibitory control function noted by **Viskontas & Holyoak**, commentators **Zook & Davalos** provide cross-sectional data for individuals

between the ages of 5 and 80+ years on the Tower of London (TOL) task. The TOL is a widely utilized measure of EF that, while dependent on WM demand, has been shown by Miyake et al. (2000), in the somewhat simpler form of the Tower of Hanoi, to also be dependent on inhibitory control. The finding that the ability to solve the task efficiently is reduced at the extremes of the life span, when cortical networks associated with the prefrontal cortex (PFC) are undergoing rapid change, provides further suggestion for the need to examine fluid cognitive ability independently of general intelligence. Indeed, this is exactly what Zook et al. (in press) did in individuals at the upper end of the life span. Consistent with some of the primary arguments of the target article, they found that fluid cognitive measures did indeed differentiate older from younger adults, and that this differentiation was present on a measure of fluid intelligence and measures of EF (the TOL and the Wisconsin Card Sorting Task [WCST]) but not crystallized intelligence. Of further interest from the perspective of the target article would be prediction from measures of fluid cognition and crystallized intelligence to aspects of social competence in older adults.

## R5. Attention

Although in combination working memory and inhibitory control appear to play a powerful role in cognitive competence, attention is an aspect of fluid cognitive functioning that was not well characterized in the target article. The commentary by **Cowan**, however, provides a very useful introduction to the study of attention and fluid cognition. Specifically, Cowan's focus on the role of attention in information storage provides a comprehensive model for what I consider to be the attention-shifting component of EF. The cognitive ability to shift attention between bits of information held in short-term store and to use attention to maintain that information in storage is a key aspect of fluid cognitive function that is not represented by working memory or inhibitory control per se.

What is also compelling in **Cowan's** approach is the explicit incorporation of relations among anterior and posterior brain regions in fluid cognition. As noted by Cowan in his commentary, and as stated in the target article, findings from brain imaging and electrophysiological recording clearly indicate the involvement of anterior, posterior, and subcortical brain regions in fluid cognitive tasks. Cowan's model details a specific role for posterior brain regions in information storage, along the lines of the phonological and visual-spatial loops in Baddeley's (1986) model. In addition to Cowan's work reviewed briefly in his commentary, work by Dehaene and collaborators also provides evidence for a parietal-frontal network in fluid cognition, in this instance in relation to the solution of simple mathematics problems and number processing (Dehaene et al. 2003; Simon et al. 2004). Work from this group suggests that distinct areas of the parietal lobe, in combination with prefrontal cortical areas, are involved in distinct types of mathematical cognitive activity. Similarly, work by Buckner (2004) indicates frontal-parietal connectivity in memory function in typical aging and dementia. Here, Cowan's emphasis on the distinction between storage and processing may be particularly

useful for understanding the role of fluid cognition in learning and memory.

## R6. An alternative position: Duncan's adaptive-coding model

As a counterpoint to the drive to differentiate working memory, inhibitory control, and attention shifting in the study of human cognitive abilities, it is necessary to consider John Duncan's adaptive-coding model (Duncan 2001; Duncan & Owen 2000). In Duncan's model, fluid cognitive processes are essentially unitary, and differentiation of working memory, inhibitory control, and attention shifting is not a realizable goal (at least as seen from the perspective of cognitive neuroscience). This is because these cognitive processes are understood to be dependent upon a shared prefrontal cortical network characterized by neurons that are highly adaptive to task demand. Specifically, as shown in findings from a number of brain imaging and single-cell recording studies, mid-dorsal lateral and ventral lateral PFC and dorsal anterior cingulate cortex (ACC) compose a cortical network comprised of neurons that are recruited by a variety of cognitive tasks. Whether in response to information maintenance, attention shifting, delayed response, response inhibition, or any of a number of fluid-type information-processing abilities, neurons in the cortical network adapt to support the behavior. In Duncan's model and data, this adaptive nature of neurons in the PFC network provides for a common processing substrate for all fluid cognitive abilities such that "working memory, selective attention, and (cognitive) control are simply three different perspectives on the same underlying processing function" (Duncan 2001, p. 824).

Although the adaptive-coding model might be characterized in some ways as overtly reductionist (i.e., if seemingly diverse aspects of fluid cognition share a common adaptive processing substrate, then they will be indistinguishable behaviorally), it is, according to Duncan, consistent with a body of clinical and brain-imaging evidence indicating the difficulty of separating fluid functions into well-specified components at the behavioral and neurological levels. At the very least, an important direction for researchers interested in the differentiation of WM, EF, and gF will be to reconcile behavioral and neuroscience data to identify unity and diversity in brain-behavior relations associated with individual differences in fluid cognitive abilities. Here the analysis by Gray et al. (2003) (as briefly described in **Burgess et al.'s** commentary) appears to be a valuable example (and one that Duncan [2003] has commented on). In that analysis, increases in levels of activation in the dorsal lateral prefrontal cortex (DLPFC) in response to a specific aspect of the task (lure trials), rather than differences in brain regions activated during less demanding aspects of the task, were related to differences in gF and WM span.

In contrast to the findings by Gray et al. (2003), however, an experiment by McDonald et al. (2000) revealed a somewhat similar finding for activation in response to a modified Stroop inhibitory control task but did so in distinct brain regions and with both positive and negative relations between brain activation and

performance. Specifically, increased activation was observed in left DLPFC in response to the instruction to name the color (the more demanding task) relative to that observed in response to the instruction to name the word (the less demanding task). No differences in activation were observed in DLPFC, however, during the response phase of the task (the actual naming of the color or the word). In contrast, in the ACC, activation was observed in the response phase of the task but not the instructional phase. Furthermore, as with DLPFC, higher levels of activation were observed in the ACC for the more demanding response, to name the color, not the word. However, whereas activation in the DLPFC during the instruction phase was inversely related to errors in the response phase, activation in the ACC during the response phase tended to be positively related to error rates.

### R7. Adaptability of adaptive coding: The role of stress and emotion

Reconciling the adaptive-coding model with behavioral and brain science models suggesting differentiation of fluid cognitive abilities is an important step in resolving the relation of fluid cognition to general intelligence. Duncan's adaptive coding model provides an overarching framework for the data he presented in a widely cited article indicating dorsal lateral prefrontal cortex to be the primary neural basis for general intelligence (cf. Duncan et al. 2000). However, interpretation of those data appears to be predicated on the assumption that  $gF = g$  and, as the numerous sources of evidence reviewed in the target article and presented in many of the commentaries indicate, this assumption is not tenable.

Furthermore, although the adaptive-coding model lends itself to a relatively straightforward interpretation regarding a neural substrate for aspects of cognition considered to be central to general intelligence, it also leads naturally to questions regarding factors that may influence the development and functioning of that substrate. In my estimation, as indicated in the target article, of strong interest here are aspects of stress and emotion that have been shown to influence neural circuitry important for fluid cognition both in human and in nonhuman animal models. However, it may be that aspects of emotion and stress are more relevant to working memory, inhibitory control, and attention shifting than to  $gF$  and to  $g$  per se. It is likely that further work can clearly elucidate relations between these aspects of experience in a way that can help to refine the differentiation of  $EF$  and  $gF$ .

The commentaries by **Demetriou, Benga, and Burgess et al.** provide valuable examples of the direction that work on emotion can take in the study of intelligence. Demetriou provides an example of the use of structural equation modeling to demonstrate the extent to which perceived competence and aspects of emotion are distinct partners in general intelligence. Of particular interest in Demetriou's analysis is that the sample is composed of adolescents. The majority of work on the structure of intelligence, and that associated with the relation of fluid cognitive abilities to  $g$ , is conducted with adults. But there are of course reasons to expect that aspects of emotion and sense of self may affect cognitive functioning differently at different

points in the life course. Adolescence is a time of rapid biological and psychological change, as is early childhood and to some extent older adulthood. Such a developmental perspective is notably lacking in much research on intelligence, and it is hoped that analyses similar to those presented by Demetriou can explicitly model developmental relations among emotionality, perceived competence, and intellectual ability in ways that will ultimately help to clearly differentiate fluid cognition from general intelligence.

The commentaries by **Benga and Kaufman & Kaufman** provide explicit endorsements of the developmental perspective in the study of fluid cognition and general intelligence. Focusing on the combined inhibitory control/working memory construct, and following the work of Posner and Rothbart (2000) using the spatial conflict task developed by Gerardi-Caulton (2000), Benga suggests what has been clearly demonstrated by Diamond (2002) – that this aspect of cognition can be differentiated early in the life span and tracked developmentally. As well, the commentator suggests that inhibitory control/working memory may be particularly amenable to the influence of early life stress, as I suggested in the target article and as Blair et al. (2005b) continue to examine among preschool children living in poverty.

**Kaufman & Kaufman**, however, strike a more cautious note regarding the differentiation of fluid cognitive abilities in children. Noting the strength of the literature in cognitive-aging research, these authors suggest that the slow maturation rate of the PFC provides for a different perspective on fluid cognition in young children. In contrast, in the target article and elsewhere, I suggest that the slower maturation rate of the PFC highlights the distinctiveness of fluid aspects of cognition in children and renders these aspects of cognitive ability particularly amenable to the influence of emotion and stress (Blair 2002). Of course, such a situation increases the already considerable challenge of trying to measure fluid cognition accurately in young children. Fluid cognitive abilities have traditionally not been measured very well by standardized test batteries; in part, for the reasoning behind Kaufman & Kaufman's commentary: the assumption that these aspects of cognition are simply not developed in young children. According to the commentators, however, there are now a number of mental test batteries that contain comprehensive fluid cognitive assessments. Although I greatly appreciate this information and expect that the measures they describe provide a wealth of valuable data, I am still not convinced that all of them have been developed with as clear a conceptualization of fluid cognitive ability, independent of general intelligence, as might be needed. In part, this is because the knowledge base on fluid cognitive abilities, particularly in children, is in a process of rapid development. No doubt the measures outlined by Kaufman & Kaufman assess key aspects of fluid cognitive abilities, but these measures may also contain assessments that are less central to fluid abilities and that will not combine in a way that can clearly measure what is most relevant to the study of the development of fluid cognition.

The role of emotionality, but not life stress, is also addressed by **Burgess et al.** and **Tzafestas**. Burgess et al. report negative relations between the behavioral activation system (BAS) subscales of Carver and White's (1994) behavioral inhibition system/behavioral activation

system (BIS/BAS) measure and brain activation in the PFC and ACC across trial types on the *n*-back working memory task. This fascinating finding suggests that high levels of approach behavior, which are thought to be associated with risk for externalizing behavior problems and are themselves associated with EF deficits in children (Blair et al. 2004; Cole et al. 1993), may be associated with reduced activation in brain areas associated with fluid cognitive abilities. Furthermore, the finding of the effect across trial types and controlling for *g*F suggests a general relation between neural activity in cortical networks associated with the PFC and a fundamental aspect of personality in young adults.

In our work on the BAS, we have shown in preschool children that high level of BAS (as measured by a version of the scale adapted for parent report) is associated with lower level of EF, lower level of hypothalamic pituitary adrenal axis arousal, and higher level of parasympathetic autonomic nervous system (ANS) reactivity (Blair et al. 2004). Similarly, Sutton and Davidson (1997) have shown that higher level of BAS in young adults is associated with greater relative left prefrontal brain activity as measured using electroencephalography (EEG). In combination, these results provide evidence for the relation of BAS to aspects of brain and physiological function important for fluid cognitive abilities. Further work is required to examine the complexity of these relations, their developmental pathways, and the extent to which high approach may be indicative of greater processing efficiency and perhaps greater fluid cognitive ability in some individuals but indicative of a more reactive personality type and reduced fluid cognition in others.

In a somewhat similar vein, **Tzafestas** presents a rather unique neural physiological model of the relation of fluid intelligence to crystallized intelligence in which emotion and goal directedness are seen to play important roles in the self-organization of neural networks underlying higher-order cognitive function. Focusing perhaps more on fluidity of neural processing rather than fluid cognitive processes per se, the role of individual experience both externally and internally generated looms large in the model. I suggest in the target article and elsewhere (Blair 2002), that high levels of stress and emotionality may lead to patterns of neural activity that serve through reciprocal relations among environment, behavior, and physiology to increasingly constrain cognition and behavior. Specifically, high levels of early life stress are thought to lead to problems with emotion regulation and to increase the likelihood of emotional reactive rather than effortful cognitive patterns of response to stimulation. In contrast to Tzafestas's model, however, I believe the neural organizational effects of early stress on cognition pertain more to fluid than to crystallized abilities. Of course, to the extent that fluid and crystallized functions are interrelated, it would perhaps be expected that emotion-related and stress-related influences on the neural physiology of fluid cognition might also be represented in crystallized skills. However, I believe such a model may be too encompassing and decontextualized, not taking into account the wide variety of experience that could lead to advances or delays in crystallized ability independent of fluid cognitive skills.

In contrast to a focus on the relation of emotion to cognition in research on personality and intelligence, it should be noted that **Anderson** articulates an alternative position

in which work on stress and emotion, let alone neuroscience, has little place in the study of intelligence. In contrast to Anderson's position, however, I believe that the careful working out of relations of brain structure and neurophysiology to distinct aspects of fluid cognition is essential. It is perhaps one way that we can come to some very detailed understanding of the constructs and in particular the role of experience in the development of cognition and personality.

Given the ubiquitous behavior genetic finding of high heritability for intelligence as well as the recent extension of this approach to gray matter volumes and IQ (Thompson et al. 2001; Toga & Thompson 2005), it is necessary to clearly establish relations among overlapping but distinct aspects of cognition and personality and overlapping but distinct neural structures and functions. This is particularly imperative given the unfortunate interpretation of heritability employed by many behavior genetic researchers to mean a fixed and unchanging aspect of the individual (for critiques, see Dickens & Flynn 2001b; Gottlieb 1998; and Wahlsten 1996). For example, the finding that gray matter volumes, particularly those in the PFC, are highly related to general intelligence, and like general intelligence, highly heritable (Thompson et al. 2001), tells us very little about the process of development or the role of experience in that process. As always, the equal-environments assumption looms large for inference derived from twin studies. This would seem particularly so for the study of brain development as principles of neural development and synaptic plasticity suggest the important role of experience in determining cortical volumes and functional connectivity.

A highly valuable behavior genetic case in point is provided by findings indicating high shared environmental influence on performance and full-scale Wechsler Intelligence Scale for Children (WISC) IQ in 7-year-old children from low socioeconomic status (SES) homes but high heritability in children from middle-SES and upper-SES backgrounds (Turkheimer et al. 2003). This evidence is on par with that of rising mean IQ in its indication that assumptions regarding the nature of the general factor and influences on it, particularly genetic influences, are in need of revision. I believe that such a revision will likely involve some incorporation of the idea that high levels of early adversity, particularly those associated with stress reactivity, impact in significant ways the development of neural structures and functions associated with fluid cognition and thereby the nature of relations among human cognitive abilities.

## R8. General intelligence: What is it? What is it not?

Which leads to what for me is one of the most pressing questions raised by the target article and addressed to one extent or another by several of the commentaries: namely, if fluid cognitive abilities, working memory, inhibitory control, and attention shifting are not *g* and perhaps not even *g*F, then what exactly is *g*? Where does the evidence reviewed leave us with respect to *g*? Several suggestions were made regarding this point. **Birney et al.** suggest *g* to be only of historical interest, and I posed the strong statement at the outset of this response suggesting a waning of the influence of *g* as an explanatory construct.

But it would seem that the relation of WM and EF to  $g$  and to  $gF$  is too strong and too seductive for  $g$  to move rapidly to the margin. There is a strong pull not only to equate WM and  $gF$  but to then think we have gotten very close to the elusive heart of general intelligence when identifying this relation.

Among the present commentators, the group represented by **Heitz et al.** stated previously that WM may be  $gF$  (Engle 2002). However, in subsequent reports and in their commentary on the target article, the authors are very clear that WM does not equal  $gF$ , stating that approximately half of the variance in  $gF$  is attributable to WM. (This finding is somewhat discrepant, in what appear to be expected ways, with that reported in a meta-analysis indicating the relation to be closer to a quarter of the variance [see Ackerman et al. 2005 and associated commentary].) What this means for definitions of  $g$  and  $gF$ , however, is not exactly clear. Heitz et al. state that they are focusing their efforts on executive control of attention, which would seem to be something along the lines of the combined working memory and inhibitory control function that appears to be a key, perhaps the key, aspect of the relation of fluid cognitive abilities to real-world competence independent of  $g$ . But, to some extent, it seems that the more rigorously one defines fluid cognition, the less clear  $g$  and  $gF$  become.

Other commentators, of course, have a different take on what is unique to  $g$  and  $gF$ . The approach of **Garlick & Sejnowski** is of particular interest in that they of all the commentators most explicitly take issue with the relation of WM and EF to  $g$  and  $gF$  (while mistakenly claiming that I describe the WCST as a measure of fluid intelligence.) I very much appreciated their insight that even the easiest of Raven's matrices items, which make limited demands on WM, are measures of fluid intelligence and that the central aspect of  $gF$  may be abstraction ability. However, it is open to question whether abstraction as a thing in itself would prove tractable as an object of study and, even if so, whether it would prove to be a higher-order construct dependent on working memory, inhibitory control, and attention shifting. Similarly, **Stanovich**, who in contrast to Garlick & Sejnowski took no issue with the idea that aspects of EF as instantiated in  $gF$  would fracture quite naturally from  $g$  and  $gC$ , proposed cognitive decoupling as the possible relevant aspect of  $gF$ . As with abstraction, this construct would seem to have high face validity, but the extent to which it would prove tractable as a measurable aspect of cognition distinct from lower-order WM and EF processes remains to be seen. However, it seems highly promising as a target of inquiry.

Furthermore, it is possible that those of us who are entranced by the relation of WM and EF to  $g$  and  $gF$  are simply barking up the wrong tree – or, more appropriately, that we have a tree of our own that we should be satisfied with and stop sniffing around the  $g$  factor. According to the analysis by **Johnson & Gottesman**, the  $gF$ - $gC$  characterization of intelligence is incorrect; Vernon's (1965) verbal-educational ( $v:ed$ ) and spatial-mechanical ( $k:m$ ) characterization of the structure of intelligence provides a more accurate fit to the data and description of what  $g$  is all about (Johnson & Bouchard 2005). Although Johnson and Bouchard's analysis appears to be very well done, it is interesting that, in order to obtain a better

fitting model with the Vernon approach, an additional memory factor at the second stratum and most importantly an additional visual-spatial ability, mental rotation factor at the third stratum were needed. The presence of the visual-spatial ability, mental rotation factor at the third stratum is fascinating in that spatial ability and mental rotation both substantially involve working memory and as such can be considered fluid cognitive functions dependent upon a prefrontal-parietal cortical network (Constanidis & Wang 2004; Smith & Jonides 1999). Accordingly, although controversial, I would suggest that perhaps the Vernon-Johnson model does indeed provide a more accurate description of the structure of intelligence to the extent that it helps to reinforce the point that reconciling the relation of fluid cognitive ability to general intelligence will continue to be a major aspect of the redefinition of what matters most in the study of human cognitive abilities. The need for adjustment of the Vernon-Johnson model to accommodate four items assessing visual-spatial ability suggests that further examinations of the Vernon structure of intelligence with test batteries containing a greater number of visual as well as verbal working memory, inhibitory control, and attention-shifting items would be warranted. My prediction for these studies is that items assessing fluid cognitive abilities will continue to cause problems for model fit.

## R9. Agree to disagree

Although I find myself in agreement with much of the commentary on the target article, there are a few points raised by some commentators that I have to agree to disagree with. Specifically, **Kovacs, Plaisted, & Mackintosh** [Kovacs et al.] question the basic thesis of dissociation. Although sympathetic to the need for further investigation of fluid skills, particularly in children, these commentators suggest that the target article provides no compelling evidence of dissociation of fluid skills from general intelligence. To a large extent, they attribute this to a perceived tendency on my part (1) to associate general intelligence with crystallized rather than fluid abilities, and (2) to regularly interchange the terms general intelligence and  $g$ , and fluid cognition and  $gF$ .

As to the first point, nothing in the text cited by **Kovacs et al.** suggests that I consider  $gC$  to be identical to  $g$ . The crucial point concerns not the relation of  $g$  to  $gC$ , a relation that no one disputes, but the absence of relations of  $gF$ , in a number of specific instances, to both  $gC$  and  $g$ . If indicators of  $gF$  are unrelated to  $g$  and also to  $gC$ , then it follows as clearly as night follows day that  $gF$  cannot be  $g$ . Which is not to discount  $g$  or  $gC$  so much as to credit aspects of  $gF$  independent of  $g$  with a hard earned legitimacy.

As to the second point concerning the interchangeable use of terms relating to aspects of cognitive function, I find myself cornered by these commentators' skillful wielding of Occam's razor. I can only plead that I find the epistemological distinction between universal and differential constructs to be a differentiation unto itself that is of questionable utility. I believe that most scientists would agree that universal and differential constructs are at least moderately interconnected, and that the differential construct serves as our best guess about the nature

of the universal construct. Although one can distinguish among the terms general intelligence and *g*, and fluid cognition and *gF*, we must allow for some interchangeable use among the terms or the research enterprise becomes more philosophic than empirical. In particular, although dissociation of two processes may or may not inform us about the correlation between them, it certainly tells us quite a bit about the relevance of the particular instance of the differential to real-world competence. Introducing the differential construct handedness into the unfortunate missing-limb analogy, it becomes quickly obvious that when an individual loses the dominant hand, be that right or left, functioning rapidly deteriorates. It is cold comfort to know that the universal construct of overall strength remains intact. I suggest that in this and most, if not all instances, it is preferable to remain rooted in the functional realm of the differential rather than the ethereal realm of the universal. I believe this to be the case particularly with intelligence research, which has spent far too much time with the ether. A very useful description of the tension between the abstract and the concrete in scientific inquiry is provided by A. N. Whitehead in his description of the Fallacy of Misplaced Concreteness (1925/1948). Although Whitehead's fallacy was formulated within a general critique of the scientific endeavor, it is particularly applicable to psychological research and to research on intelligence specifically.

Similarly, as a student of the history of science (B.A. 1984, McGill University), I very much enjoyed **Voracek's** characterization of the independent fluid cognitive construct as a phlogiston theory. Although in hindsight, the scientific past can appear as a repository of cockamamie theories and failed ideas, such a view provides a highly inaccurate picture of the process of scientific inquiry. Phlogiston, for example, represented a logical extension of alchemical thinking and principles that was, as is its successor, modern chemistry, based in the empirical approach. Certainly one can discern a positivist and progressive history to the advance of science, but it is a history characterized by many twists and turns. Accordingly, to my way of thinking, as an explanatory construct, the theory of general intelligence possesses a much greater similarity to phlogiston than does work on fluid cognition. In fact, the *g* factor, as a poorly defined entity emerging from factor analysis of diverse tests of mental ability, bears a striking resemblance to the hypothetical phlogistic material used to explain the occurrence of combustion. Namely, prior to the identification of oxygen and the mechanisms of combustion, phlogiston served as a working explanation for the effect that lost its utility only when it ceased to be consistent with observation and experiment. At that point, due mainly to unceasing defense by its champions, it increasingly became more of an impediment to scientific progress than anything else.

Unfortunately a phlogiston-like situation appears to be the case with some of the research on *g*. I take as a case in point **Voracek's** seeming fascination with the Flynn effect, and what seems to be an overarching desire in his commentary to discredit this well-established phenomenon. The commentator's focus on this one piece of evidence supporting the dissociation of fluid cognition from general intelligence is of further interest in that the data that he offers to refute the effect are derived from a sample of psychiatric patients. The target article,

however, reviews a considerable body of evidence indicating that a number of psychiatric disorders, in particular schizophrenia, but also more common disorders, such as anxiety and depression, which presumably would make up the bulk of the author's sample, are frequently characterized by fluid cognitive deficits in the presence of crystallized ability and general intelligence in the normal range. Accordingly, the absence of the generational effect on fluid cognition in Voracek's data would seem to provide additional support for the overall hypothesis of dissociation. The absence of the increase in his sample would be expected.

## R10. Conclusion

Without question, further conceptual and empirical advances are needed to address relations among fluid cognitive abilities and relations of fluid cognition to general intelligence. In this work, I suggest that a developmental neuroscience approach that clearly incorporates the role of emotion-related and stress-related processes in a comprehensive understanding of the structure and function of neural systems associated with fluid cognitive abilities is most likely to yield findings of lasting basic and applied science utility. Furthermore, at the outset of this essay, I raised the possibility that, due to an increasing lack of specificity, the general factor of intelligence is of decreasing utility as an explanatory construct and that an expanded and revised theory of intelligence is needed that can reconcile traditional conceptions of intelligence with new data and perspectives on fluid cognition. Certainly what this reconciliation will look like remains to be seen. However, it may be that much of the information necessary for the endeavor is currently available. In particular, although researchers have been somewhat less than enthusiastic about the moderate correlation between the general factor and measures of inspection time and reaction time (IT/RT), it may be that these relations tell an important part of the story. Given the presence of sociological and neurobiological influences on fluid cognition and the similarity of fluid cognition to general intelligence, IT/RT measures, as indicators of general speediness and faster, more efficient brains, may be what *g* as traditionally conceived is really all about. Such a conclusion for *g* may be more modest than many may have hoped for, but if correct, the result could lead one to contemplate a complex set of associations among multiple variables relating to neural efficiency, neural structure, emotion, stress, and experience. Such a complex model, although in need of further theoretical underpinnings and empirical support, may perhaps be able to adequately account for the seemingly all-encompassing nature of general intelligence, as traditionally conceived. To some extent, it would seem that the general factor as conceptualized over the past 100 years or more has simply proven too monolithic in its current form to be of continued scientific value. This of course in no way changes the fact that the construct embodies a great deal of what matters most in the study of human behavior. Indeed, it suggests that if the construct as it is currently known is beginning to fade into the scientific sunset, it certainly isn't going with a bang, but neither is it going

with a whimper. At best, the report of its death would have to be greatly exaggerated.

## References

**The letters “a” and “r” before author’s initials stand for target article and response references, respectively.**

- Ackerman, P. L., Beier, M. E. & Boyle, M. O. (2005) Working memory and intelligence: The same or different constructs? *Psychological Bulletin* 131:30–60. [rCB, RPH]
- Allman, J. M., Hakeem, A., Erwin, J., Nimchinsky, E. & Hof, P. (2001) The anterior cingulate cortex: The evolution of an interface between emotion and cognition. *Annals of the New York Academy of Sciences* 935:107–17. [aCB]
- Amminger, G. P., Schlogelhofer, M., Lehner, T., Looser Ott, S., Friedrich, M. H. & Aschauer, H. N. (2000) Premorbid performance IQ deficit in schizophrenia. *Acta Psychiatrica Scandinavica* 102:414–22. [aCB]
- Anderson, M. (2000) An unassailable defense of g but a siren-song for theories of intelligence. *Psycoloquy*, 00.11.013.intelligence-g-factor.2S.anderson. <ftp://ftp.princeton.edu/pub/harnad/Psycoloquy/2000.volume.11/>. [MA]
- (2001) Annotation: Conceptions of intelligence. *Journal of Child Psychology and Psychiatry* 42(3):287–98. <ftp://ftp.princeton.edu/pub/harnad/Psycoloquy/2000.volume.11/>. [MA, RMF]
- (2005) Cortex forum on the concept of general in neuropsychology. *Cortex* 41:99–100. Available at: <http://www.cortex-online.org/cortex.asp?action=toArticles&folderID=148>. [MA]
- Ando, J., Ono, Y. & Wright, M. J. (2001) Genetic structure of spatial and verbal working memory. *Behavior Genetics* 31:615–24. [aCB]
- Ashton, M. C., Lee, K. & Vernon, P. A. (2001) Which is the real general intelligence? A reply to Robinson (1999). *Personality and Individual Differences* 1353–59. [aCB]
- Bachevalier, J., Alvarado, M. C. & Malkova, L. (1999) Memory and socioemotional behavior in monkeys after hippocampal damage incurred in infancy or in adulthood. *Biological Psychiatry* 46:329–39. [aCB]
- Baddeley, A. (1986) *Working memory*. Oxford Psychology Series, No. 11. Oxford University Press/Clarendon Press. [aCB, NC]
- (2000) The episodic buffer: A new component of working memory? *Trends in Cognitive Sciences* 4:417–23. [NC]
- Baddeley, A., Chincotta, D. & Adlam, A. (2001) Working memory and the control of action: Evidence from task switching. *Journal of Experimental Psychology: General* 130:641–57. [KES]
- Balkenius, C. (2000) Attention, habituation and conditioning: Toward a computational model. *Cognitive Science Quarterly* 1(2):171–214. [EST]
- Barkeley, R. A. (1997) Behavioral inhibition, sustained attention, and executive function: Constructing a unifying theory of ADHD. *Psychological Bulletin* 121:65–94. [aCB]
- Barrett, P. (2000) Intelligence, psychometrics, g, and mental abilities: Quantitative methodology dressed as science. *Psycoloquy*, 00.11.046.intelligence-g-factor.45.barrett. <ftp://ftp.princeton.edu/pub/harnad/Psycoloquy/2000.volume.11/>. [MA]
- Bechara, A. (2004) The role of emotion in decision-making: Evidence from neurological patients with orbitofrontal damage. *Brain and Cognition* 55:30–40. [aCB]
- Bechara, A., Damasio, H., Damasio, A. & Lee, G. P. (1999) Different contributions of the human amygdala and ventromedial prefrontal cortex to decision-making. *Journal of Neuroscience* 19:5473–81. [aCB]
- 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* 6:215–25. [aCB]
- Bedwell, J. S., Keller, B., Smith, A. K., Hamburger, S., Kumra, S. & Rapoport, J. L. (1999) Why does postpsychotic IQ decline in childhood onset schizophrenia? *American Journal of Psychiatry* 156:1996–97. [aCB]
- Benga, O. (2001) Sociocognitive control of emotions: The case of early attachment. In: *Development and cognition*, ed. O. Benga & M. Miclea. Editura Presa Universitara Clujeana. [OB]
- (2004) *Development of social cognition in children* [in Romanian]. ASCR (Asociația Română de Științe Cognitive, Publishing House of the Romanian Association of Cognitive Sciences). [OB]
- Berlin, L. (2003) *The role of inhibitory control and executive functioning in hyperactivity/ADHD: Comprehensive summaries of Uppsala dissertations from the Faculty of Social Sciences 120*. Acta Universitatis Upsalensis. [aCB]
- Bertolino, A., Roffman, J. L., Lipska, B. K., van Gelderen, P., Olson, A. & Weinberger, D. R. (2002) Reduced N-acetylaspartate in prefrontal cortex of adult rats with neonatal hippocampal damage. *Cerebral Cortex* 12:983–90. [aCB]
- Bertolino, A., Saunders, R. C., Mattay, V. S., Bachevalier, J., Frank, J. A. & Weinberger, D. R. (1997) Altered development of prefrontal neurons in rhesus monkeys with neonatal mesial temporo-limbic lesions: A proton magnetic resonance spectroscopic imaging study. *Cerebral Cortex* 7:740–48. [aCB]
- Blair, C. (2002) School readiness: Integrating cognition and emotion in a neurobiological conceptualization of child functioning at school entry. *American Psychologist* 57:111–27. [aCB]
- Blair, C., Gamsom, E., Thorne, S. & Baker, D. (2005a) Rising mean IQ: Cognitive demand of mathematics education for young children, population exposure to formal schooling, and the neurobiology of the prefrontal cortex. *Intelligence* 33:93–106. [MV]
- Blair, C., Granger, D. & Razza, R. P. (2005b) Cortisol reactivity is positively related to executive function in preschool children attending Head Start. *Child Development* 76:554–67. [rCB]
- Blair, C., Peters, R. & Granger, D. (2004) Physiological and neuropsychological correlates of approach/withdrawal behavior in preschool: Further examination of the BIS/BAS scales for young children. *Developmental Psychobiology* 45:113–24. [rCB]
- Borsboom, D., Mellenbergh, G. J. & van Heerden, J. (2003) The theoretical status of latent variables. *Psychological Review* 110(2):203–19. [DPB]
- (2004) The concept of validity. *Psychological Review* 111(4):1061–71. [DPB]
- Braun, K., Lange, E., Metzger, M. & Poeppel, G. (1999) Maternal separation followed by early social deprivation affects the development of monoaminergic fiber systems in the medial prefrontal cortex of *Octodon degus*. *Neuroscience* 95:309–18. [aCB]
- Braver, T. S. & Barch, D. M. (2002) A theory of cognitive control, aging cognition, and neuromodulation. *Neuroscience and Biobehavioral Reviews* 26:809–17. [aCB, NAZ]
- Braver, T. S., Barch, D. M. & Cohen, J. D. (1999) Cognition and control in schizophrenia: A computational model of dopamine and prefrontal function. *Biological Psychiatry* 46:312–28. [aCB]
- Braver, T. S., Barch, D. M., Kelley, W. M., Buckner, R. L., Cohen, N. J., Miezin, F. M., Snyder, A. Z., Ollinger, J. M., Akbudak, E., Conturo, R. E. & Petersen, S. E. (2001) Direct comparison of prefrontal cortex regions engaged by working and long-term memory tasks. *NeuroImage* 14:48–59. [aCB]
- 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. [aCB]
- Bredy, T. W., Humpartzoomian, R. A., Cain, D. P. & Meany, M. J. (2003) Partial reversal of the effect of maternal care on cognitive function through environmental enrichment. *Neuroscience* 188:571–76. [aCB]
- Breitenstein, C., Jansen, A., Deppe, M., Foerster, A. F., Sommer, J., Wolbers, T. & Knecht, S. (2005) Hippocampus activity differentiates good from poor learners of a novel lexicon. *NeuroImage* 25:958–68. [MW]
- Brody, N. (1992) *Intelligence*, 2nd edition. Academic Press. [DG]
- Brozoski, T. J., Brown, R. M., Rosvold, H. E. & Goldman, P. S. (1979) Cognitive deficits caused by regional depletion of dopamine in the prefrontal cortex of rhesus monkey. *Science* 205:929–32. [aCB]
- Buckner, R. L. (2004) Memory and executive function in aging and AD: Multiple factors that cause decline and reserve factors that compensate. *Neuron* 44:195–208. [rCB]
- Buckner, R. L. & Wheeler, M. E. (2001) The cognitive neuroscience of remembering. *Nature Reviews: Neuroscience* 2:311–14. [rCB]
- Bull, R. & Scerif, G. (2001) Executive functioning as a predictor of children’s mathematics ability: Inhibition, switching, and working memory. *Developmental Neuropsychology* 19:273–93. [aCB]
- Bunce, D. (2003) Cognitive support at encoding attenuates age differences in recollective experience among adults of lower frontal lobe function. *Neuropsychology* 17(3):353–61. [NAZ]
- Burbaud, P., Degreze, P., Lafon, P., Franconi, J., Bouligand, B., Bioulac, B., Caille, J. & Allard, M. (1995) Lateralization of prefrontal activation during internal mental calculation: A functional magnetic imaging study. *Journal of Neurophysiology* 74:2194–200. [aCB]
- Burgess, G. C., Gray, J. R., Conway, A. R. A. & Braver, T. S. (2005) Relationships among fluid intelligence, working memory span, and brain activity during high-interference trials. Poster presented at the 12th Annual Meeting of the Cognitive Neuroscience Society, New York, NY, April 2005. [GCB]
- Burgess, N., Becker, S., King, J. A. & O’Keefe, J. (2001) Memory for events and their spatial context: Models and experiments. *Philosophical Transactions of the Royal Society of London B* 356:1493–503. [EST]
- Bush, G., Luu, P. & Posner, M. I. (2000) Cognitive and emotional influences in the anterior cingulate cortex. *Trends in Cognitive Sciences* 4:215–22. [OB, aCB]
- Cabeza, R., Anderson, N. D., Locantore, J. K. & McIntosh, A. R. (2002) Aging gracefully: Compensatory brain activity in high performing older adults. *NeuroImage* 17:1394–402. [aCB]

- Caldji, C., Diorio, J. & Meaney, M. J. (2000a) Variations in maternal care in infancy regulate the development of stress reactivity. *Biological Psychiatry* 48:1164–74. [aCB]
- Caldji, C., Francis, D., Sharma, S., Plotsky, P. M. & Meaney, M. J. (2000b) The effects of early rearing environment on the development of GABA<sub>A</sub> and central benzodiazepine receptor levels and novelty-induced fearfulness in the rat. *Neuropsychopharmacology* 22:219–29. [aCB]
- Callicott, J., Matay, V., Bertolino, A., Finn, K., Coppola, R., Frank, J., Goldberg, T. & Weinberger, D. (1999) Physiological characteristics of capacity constraints in working memory as revealed by functional MRI. *Cerebral Cortex* 9:20–26. [aCB]
- Carlson, S. M. (2003) Executive function in context: Development, measurement, theory and experience. *Monographs of the Society for Research in Child Development* 68:138–51. [RMF]
- Carlson, S. M. & Moses, L. J. (2001) Individual differences in inhibitory control and children's theory of mind. *Child Development* 72:1032–53. [OB]
- Carlson, S. M., Mandell, D. J. & Williams, L. (2004) Executive function and theory of mind: Stability and prediction from ages 2 to 3. *Developmental Psychology* 40:1105–22. [RMF]
- Carpenter, P. A., Just, M. A. & Reichle, E. D. (2000) Working memory and executive function: Evidence from neuroimaging. *Current Opinion in Neurobiology* 10:195–99. [aCB]
- 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* 97:404–31. [aCB]
- Carroll, J. B. (1993) *Human cognitive abilities: A survey of factor-analytic studies*. Cambridge University Press. [DPB, aCB, WJ, KES, MV]
- (1996) A three-stratum theory of intelligence: Spearman's contribution. In: *Human abilities: Their nature and measurement*, ed. I. Dennis & P. Tapsfield, pp. 1–18. Erlbaum. [aCB]
- (2003) The higher-stratum structure of cognitive abilities: Current evidence supports *g* and about ten broad factors. In: *The scientific study of general intelligence: Tribute to Arthur R. Jensen*, ed. H. Nyborg, Elsevier Science/Pergamon. [KK, MV]
- Carruthers, P. (2002) The cognitive functions of language. *Behavioral and Brain Sciences* 25:657–726. [KES]
- Caruso, J. C. (2001) Reliable component analysis of the Stanford-Binet: Fourth edition for 2- to 6-year-olds. *Psychological Assessment* 13:261–66. [aCB]
- Carver, C. S. & White, T. (1994) Behavioral inhibition, behavioral activation, and affective responses to impending reward and punishment: The bis/bas scales. *Journal of Personality and Social Psychology* 67:319–33. [GCB, rCB]
- Case, R. (1992) The role of the frontal lobes in the regulation of cognitive development. *Brain and Cognition* 20:51–73. [RMF]
- (1995) Capacity-based explanations of working memory growth: A brief history and reevaluation. In: *Memory performance and competencies: Issues in growth and development*, ed. F. E. Weinert & W. Schneider, pp. 23–44. Erlbaum. [NC]
- Case, R. & Mueller, M. P. (2001) Differentiation, integration, and covariance mapping as fundamental processes in cognitive and neurological growth. In: *Mechanisms of cognitive development: Behavioral and neural perspectives*, ed. J. L. McClelland & R. S. Siegler, pp. 185–219. Erlbaum. [RMF]
- Case, R., Demetriou, A., Platsidou, M. & Kazi, S. (2001) Integrating concepts and tests of intelligence from the differential and developmental traditions. *Intelligence* 29:307–36. [RMF]
- Cattell, R. B. (1943) The measurement of adult intelligence. *Psychological Bulletin* 40:143–93. [WJ]
- (1963) Theory of fluid and crystallized intelligence: A critical experiment. *Journal of Educational Psychology* 54:1–22. [WJ, KES]
- (1971) *Abilities: Their structure, growth, and action*. Cambridge University Press. [aCB, WJ, IVV]
- (1998) Where is intelligence? Some answers from the triadic theory. In: *Human cognitive abilities in theory and practice*, ed. J. J. McArdle & R. W. Woodcock, pp. 29–38. Erlbaum. [KES]
- Chambers, R. A., Moore, J., McEvoy, J. P. & Levin, E. D. (1996) Cognitive effects of neonatal hippocampal lesions in a rat model of schizophrenia. *Neuropsychopharmacology* 15:587–94. [aCB]
- Clinton, S. M. & Meador-Woodruff, J. H. (2004) Thalamic dysfunction in schizophrenia: Neurochemical, neuropathological, and in vivo imaging abnormalities. *Schizophrenia Research* 69:237–53. [MW]
- 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: *Prospective memory: Theory and applications*, ed. M. Brandimonte, G. Einstein & M. McDaniel, pp. 267–93. Erlbaum. [aCB]
- 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. [aCB]
- Cohen, J. D., Perstein, W. M., Braver, T. S., Nystrom, L. E., Noll, D. C., Jonides, J. & Smith, E. E. (1997) Temporal dynamics of brain activation during a working memory task. *Nature* 386:604–608. [aCB]
- Cole, P. M., Usher, B. A. & Cargo, A. P. (1993) Cognitive risk and its association with risk for disruptive behavior disorder in preschoolers. *Journal of Clinical Child Psychology* 22:154–64. [rCB]
- Colom, R., Lluís-Font, J. P. & Andrés-Pueyo, A. (2005) The generational intelligence gains are caused by decreasing variance in the lower half of the distribution: Supporting evidence for the nutrition hypothesis. *Intelligence* 33:83–91. [MV]
- Colom, R., Rebollo, I., Palacios, A., Juan-Espinosa, M. & Kyllonen, P. C. (2004) Working memory is (almost) perfectly predicted by *g*. *Intelligence* 32:277–96. [DPB, aCB, RPH, KES]
- Constanidis, C. & Wang, X. J. (2004) A neural circuit basis for spatial working memory. *Neuroscientist* 10:553–65. [rCB]
- Conway, A. R. A., Cowan, N., Bunting, M. F., Theriault, D. J. & Minkoff, S. R. B. (2002) A latent variable analysis of working memory capacity, short-term memory capacity, processing speed, and general fluid intelligence. *Intelligence* 30:163–83. [aCB]
- Conway, A. R. A., Kane, M. J. & Engle, R. W. (2003) Working memory capacity and its relation to general intelligence. *Trends in Cognitive Sciences* 7(12):547–52. [DPB, aCB, RPH, KES]
- Cosmides, L. & Tooby, J. (2000) Consider the source: The evolution of adaptations for decoupling and metarepresentation. In: *Metarepresentations: A multidisciplinary perspective*, ed. D. Sperber, pp. 53–115. Oxford University Press. [KES]
- Cowan, N. (1988) Evolving conceptions of memory storage, selective attention, and their mutual constraints within the human information processing system. *Psychological Bulletin* 104:163–91. [NC]
- (1995) *Attention and memory: An integrated framework*. Oxford Psychology Series, No. 26. Oxford University Press. [NC]
- (1999) An embedded-processes model of working memory. In: *Models of Working Memory: Mechanisms of active maintenance and executive control*, ed. A. Miyake & P. Shah, pp. 62–101. Cambridge University Press. [NC]
- (2001) The magical number 4 in short-term memory: A reconsideration of mental storage capacity. *Behavioral and Brain Sciences* 24:87–185. [NC]
- Cowan, N., Chen, Z. & Rouder, J. N. (2004) Constant capacity in an immediate serial-recall task: A logical sequel to Miller (1956). *Psychological Science* 15:634–40. [NC]
- Cowan, N., Elliott, E. M., Scott Saults, J., Morey, C. C., Mattox, S., Hismjatullina, A. & Conway, A. R. (2005) On the capacity of attention: Its estimation and its role in working memory and cognitive aptitudes. *Cognitive Psychology* 51(1):42–100. [NC]
- Craik, F. I. M., Morris, R. G. & Gick, M. L. (1990) Adult age differences in working memory. In: *Neuropsychological impairments of short-term memory*, ed. G. Vallar & T. Shallice, pp. 247–67. Cambridge University Press. [IVV]
- Crawford, J. R., Deary, I., Allan, K. & Gustafsson, J.-E. (1998) Evaluating competing models of the relationship between inspection time and intelligence. *Intelligence* 26:27–42. [aCB]
- Cronbach, L. J. (1957) The two disciplines of scientific psychology. *American Psychologist* 12:671–84. [GCB]
- Damasio, A. R. (1985) The frontal lobes. In: *Clinical neuropsychology*, ed. K. M. Heilman & E. Valenstein, 2nd edition, pp. 339–75. Oxford University Press. [IVV]
- (1994) *Descartes' error: Emotion, reason, and the human brain*. Grosset/Putnam. [aCB]
- Davidson, R. J. (2002) Anxiety and affective style: Role of prefrontal cortex and amygdala. *Biological Psychiatry* 51:68–80. [aCB]
- Davidson, R. J., Putnam, K. M. & Larson, C. L. (2000) Dysfunction in the neural circuitry of emotion regulation: A possible prelude to violence. *Science* 289:591–94. [aCB]
- Dehaene, S., Piazza, M., Pinel, P. & Cohen, L. (2003) Three parietal circuits for number processing. *Cognitive Neuropsychology* 20:487–506. [rCB]
- de Jong, P. & Das-Smaal, E. A. (1995) Attention and intelligence: The validity of the Start Counting test. *Journal of Educational Psychology* 87:80–92. [aCB]
- de Kloet, E. R., Oitzl, M. S. & Joels, M. (1999) Stress and cognition: Are corticosteroids good or bad guys? *Trends in Neuroscience* 22:422–26. [aCB]
- Demetriou, A. (2004) Mind, intelligence, and development: A cognitive, developmental, and differential theory of intelligence. In: *Developmental change: Theories, models and measurement*, ed. A. Demetriou & A. Raftopoulos, pp. 21–73. Cambridge University Press. [AD]
- Demetriou, A. & Andreou, M. (in preparation) Cognition, emotions, and personality: Towards an integrated model. [AD]
- Demetriou, A. & Kazi, S. (submitted) Processing efficiency, reasoning, and self-awareness in *g*. [AD]
- Dennett, D. C. (1984) *Elbow room: The varieties of free will worth wanting*. MIT Press. [KES]

- (1996) *Kinds of minds: Toward an understanding of consciousness*. Basic Books. [KES]
- Diamond, A. (2002) Normal development of prefrontal cortex from birth to young adulthood: Cognitive functions, anatomy, and biochemistry. In: *Principles of frontal lobe function*, pp. 466–503, ed. D. Stuss & R. Knight. Oxford University Press. [rCB]
- Diamond, A. & Herzberg, C. (1996) Impaired sensitivity to visual contrast in children treated early and continuously for phenylketonuria. *Brian* 119:523–38. [aCB]
- 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*, Vol. 62, No. 4, Serial No. 252. [aCB]
- Dickens, W. T. & Flynn, J. R. (2001a) Great leap forward: A new theory of intelligence. *New Scientist*, 21 April, 2001: 44–47. [JRF]
- (2001b) Heritability estimates versus large environmental effects: The IQ paradox resolved. *Psychological Review* 108:346–69. [arCB, JRF]
- Dienes, Z. & Perner, J. (1999) A theory of implicit and explicit knowledge. *Behavioral and Brain Sciences* 22:735–808. [KES]
- Diorio, D., Viau, V. & Meaney, M. J. (1993) The role of medial prefrontal cortex (cingulate gyrus) in the regulation of hypothalamic-pituitary-adrenal responses to stress. *Journal of Neuroscience* 13:3839–47. [aCB]
- Drevets, W. C. & Raichle, M. E. (1998) Reciprocal suppression of regional cerebral blood flow during emotional versus higher cognitive processes: Implications for interactions between emotion and cognition. *Cognition and Emotion* 12:353–85. [aCB]
- Duncan, J. (2001) An adaptive coding model of neural function in the prefrontal cortex. *Nature Reviews: Neuroscience* 2:820–29. [arCB]
- (2003) Intelligence tests predict brain response to demanding task events. *Nature Neuroscience* 6:207–208. [rCB]
- Duncan, J. & Owen, A. M. (2000) Common regions of the human frontal lobe recruited by diverse cognitive demands. *Trends in Neurosciences* 23:475–83. [rCB]
- Duncan, J., Burgess, P. & Emslie, H. (1995) Fluid intelligence after frontal lobe lesions. *Neuropsychologia* 33:261–68. [aCB, RPH, KES, IVV, NAZ]
- Duncan, J., Emslie, H., Williams, P., Johnson, R. & Freer, C. (1996) Intelligence and the frontal lobe: The organization of goal-directed behavior. *Cognitive Psychology* 30:257–303. [KES]
- 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* 289:457–60. [arCB]
- Durstewitz, D. & Seamans, J. K. (2002) The computational role of dopamine D1 receptors in working memory. *Neural Networks* 15:561–72. [aCB]
- Edelman, G. M. (2004) *Wider than the sky: The phenomenal gift of consciousness*. Yale University Press. [EST]
- Egan, M. F., Goldberg, T. E., Gscheidle, T., Weirich, M., Rawlings, R., Hyde, T. M., Bigelow, L. & Weinberger, D. R. (2001) Relative risk for cognitive impairment in siblings of patients with schizophrenia. *Biological Psychiatry* 50:98–107. [aCB]
- Elliott, C. D. (1990) *Differential ability scales*. Psychological Corporation. [JCK]
- Embreton, S. (1995) The role of working memory capacity and general control processing in intelligence. *Intelligence* 20:169–89. [aCB]
- Engle, R. W. (2002) Working memory capacity as executive attention. *Current Directions in Psychological Science* 11:19–23. [rCB, KES]
- Engle, R. W., Kane, M. J. & Tuholski, S. W. (1999a) Individual difference in working memory capacity and what they tell us about controlled attention, general fluid intelligence, and function of the prefrontal cortex. In: *Models of working memory: Mechanisms of active maintenance and executive control*, ed. A. Miyake & P. Shah, pp. 102–34. Cambridge University Press. [DPB]
- Engle, R. W., Tuholski, S. W., Laughlin, J. E. & Conway, A. R. (1999b) Working memory, short-term memory, and general fluid intelligence: A latent-variable approach. *Journal of Experimental Psychology: General* 128(3):309–31. [DPB, aCB, RPH]
- Erickson, K., Drevets, W. & Schulkin, J. (2003) Glucocorticoid regulation of diverse cognitive functions in normal and pathological emotional states. *Neuroscience and Biobehavioral Reviews* 27:233–46. [aCB]
- Espy, K. A., Kaufmann, 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* 41:178–99. [aCB]
- 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* 31:246–62. [aCB]
- Evans, J. St. B. T. & Over, D. E. (2004) *If*. Oxford University Press. [KES]
- Fan, J., Fossella, J. A., Sommer, T., Wu, Y. & Posner, M. I. (2003) Executive attention: Imaging and genetic analysis. Paper presented at the Annual Meeting of the Cognitive Neuroscience Society, New York, NY, 2003. Available at: [http://140.251.58.136/%7Ejfan/online\\_papers/CNS2003\\_fMRI\\_genetic.pdf](http://140.251.58.136/%7Ejfan/online_papers/CNS2003_fMRI_genetic.pdf). [OB]
- Fernández-Ballesteros, R., Juan-Espinoso, M. & Abad, F. J. (2001) Sociohistorical changes and intelligence gains. In: *Environmental effects on cognitive abilities*, ed. R. J. Sternberg & E. L. Grigorenko, pp. 383–424. Erlbaum. [MV]
- Flanagan, D. P. & Ortiz, S. O. (2001) *Essentials of cross-battery assessment*. Wiley. [JCK]
- Flanagan, D. P., McGrew, K. & Ortiz, S. O. (2000) *The Wechsler intelligence scales and gF-gC theory: A contemporary approach to interpretation*. Allyn & Bacon. [aCB]
- Flavell, J. H., Miller, P. H. & Miller, S. A. (2002) *Cognitive development*, 4th edition. Prentice Hall. [RMF]
- Flynn, J. R. (1984) The mean IQ of Americans: Massive gains 1932 to 1978. *Psychological Bulletin* 95:29–51. [aCB, MV]
- (1987) Massive IQ gains in 14 nations: What IQ tests really measure. *Psychological Bulletin* 101:171–91. [aCB, MV]
- (1998a) IQ gains over time: Toward finding the causes. In: *The rising curve: Long-term gains in IQ and related measures*, ed. U. Neisser, pp. 25–66. American Psychological Association. [MV]
- (1998b) Israeli military IQ tests: Gender differences small; IQ gains large. *Journal of Biosocial Science* 30:541–53. [MV]
- (1998c) WAIS-III and WISC-III: IQ gains in the United States from 1972 to 1995: How to compensate for obsolete norms. *Perceptual and Motor Skills* 86:1231–39. [MV]
- (1999) Searching for justice: The discovery of IQ gains over time. *American Psychologist* 54:5–20. [aCB, MV]
- (2003) Movies about intelligence: The limitations of g. *Current Directions in Psychological Science* 12:95–99. [JRF]
- (in press) Efeito Flynn: Repensando a inteligência e seus efeitos [The Flynn effect: Rethinking intelligence and what affects it]. In: *Introdução à Psicologia das Diferenças Individuais [Introduction to the psychology of individual differences]*, ed. C. Flores-Mendoza & R. Colom. ArtMed. (English translation available from author: jim.flynn@stonebow.otago.ac.nz) [JRF]
- Francis, D. D., Caldi, C., Champagne, F., Plotsky, P. M. & Meaney, M. J. (1999a) The role of corticotropin-releasing factor-norepinephrine systems in mediating the effects of early experience on the development of behavioral and endocrine responses to stress. *Biological Psychiatry* 46:1153–66. [aCB]
- Francis, D., Diorio, J., Liu, D. & Meaney, M. J. (1999b) Nongenomic transmission across generations of maternal behavior and stress responses in the rat. *Science* 286:1155–58. [aCB]
- Francis, D. D., Diorio, J., Plotsky, P. M. & Meaney, M. J. (2002) Environmental enrichment reverses the effects of maternal separation on stress reactivity. *Journal of Neuroscience* 22:7840–43. [aCB]
- Fry, A. & Hale, S. (1996) Processing speed, working memory, and fluid intelligence: Evidence for a developmental cascade. *Psychological Science* 7:237–41. [NAZ]
- Garavan, H. (1998) Serial attention within working memory. *Memory and Cognition* 26:263–76. [NC]
- Garcia, R., Vouimba R.-M., Baudry, M. & Thompson, R. F. (1999) The amygdala modulates prefrontal cortex activity relative to conditioned fear. *Nature* 402:294–96. [aCB]
- Garlick, D. (2002) Understanding the nature of the general factor of intelligence: The role of individual differences in neural plasticity as an explanatory mechanism. *Psychological Review* 109:116–36. [aCB, DG]
- Gauvain, M. (2001) *The social context of cognitive development*. The Guilford Press. [RMF]
- Geary, D. C. (2005) *The origin of the mind: Evolution of brain, cognition, and general intelligence*. American Psychological Association. [KES]
- Gerardi-Caulton, G. (2000) Sensitivity to spatial conflict and the development of self-regulation in children 24–36 months of age. *Developmental Science* 3(4):397–404. [OB, rCB]
- Glushakov, A. V., Dennis, D. M., Morey, T. E., Sumners, C., Cucchiara, R. F., Seubert, C. N. & Martynyuk, A. E. (2002) Specific inhibition of N-methyl-D-aspartate receptor function in rat hippocampal neurons by L-phenylalanine at concentrations observed during phenylketonuria. *Molecular Psychiatry* 7:359–67. [aCB]
- Gogtay, N., Giedd, J. N., Lusk, L., Hayashi, K. M., Greenstein, D., Vaituzis, A. C., Nugent, T. F., Herman, D. H., Clasen, L. S., Toga, A. W., Rapoport, J. L. & Thompson, P. M. (2004) Dynamic mapping of human cortical development during childhood through early adulthood. *Proceedings of the National Academy of Sciences USA* 101:8174–79. [aCB]
- Goldberg, T., Berman, K., Fleming, K., Ostrem, J., Van Horn, J., Esposito, G., Mattay, V., Gold, J. & Weinberger, D. (1998) Uncoupling cognitive workload and prefrontal cortical physiology: A PET rCBF study. *NeuroImage* 7:296–303. [aCB]
- Golden, C. J. (1981) *Diagnosis and rehabilitation in clinical neuropsychology*. Charles C. Thomas. [JCK]

## References/Blair: How similar are fluid cognition and general intelligence?

- Goldman-Rakic, P. S. (1999) The physiological approach: Functional architecture of working memory and disordered cognition in schizophrenia. *Biological Psychiatry* 46:650–61. [aCB]
- Gottesman, I. I. (1997) Twins – en route to QTLs for cognition. *Science* 276:1522–23. [WJ]
- Gottesman, I. I. & Gould, T. D. (2003) The endophenotype concept in psychiatry: Etymology and strategic intentions. *American Journal of Psychiatry* 160:636–45. [WJ]
- Gottfredson, L. S. (1997) Why g matters: The complexity of everyday life. *Intelligence* 24:79–132. [DG, WJ]
- Gottlieb, G. (1998) Normally occurring environmental and behavioral influences on gene activity: From central dogma to probabilistic epigenesis. *Psychological Review* 105:792–802. [rCB]
- Gottlieb, G., Wahlsten, D. & Lickliter, R. (1998) The significance of biology for human development: A developmental psychobiological systems view. In: *Handbook of child psychology, vol. 1, Theory*, ed. R. Lerner, pp. 233–73. Wiley. [aCB]
- Gould, E. & Tanapat, P. (1999) Stress and hippocampal neurogenesis. *Biological Psychiatry* 46:1472–79. [aCB]
- Grant, S. G. N. (2003) An integrative neuroscience program linking mouse genes to cognition and disease. In: *Behavioral genetics in the post-genomic era*, ed. R. Plomin, J. C. DeFries, I. W. Craig & R. McGuffin, pp. 123–38. American Psychological Association. [WJ]
- Gray, J. R., Burgess, G. C., Schaefer, A., Yarkoni, T., Larsen, R. J. & Braver, T. S. (in press) Affective personality differences in neural processing efficiency confirmed using fMRI. *Cognitive, Affective and Behavioral Neuroscience*. [GCB]
- Gray, J. R., Chabris, C. F. & Braver, T. S. (2003) Neural mechanisms of general fluid intelligence. *Nature Neuroscience* 6:316–22. [arCB, GCB, KES]
- Greenfield, P. M. (1997) You can't take it with you: Why ability assessments don't cross cultures. *American Psychologist* 52:1115–24. [aCB]
- Griffiths, P. V., Demelweek, C., Fay, N., Robinson, P. H. & Davidson, D. C. (2000) Wechsler subscale IQ and subtest profile in early treated phenylketonuria. *Archives of Disease in Childhood* 82:209–15. [aCB]
- Grigorenko, E. L. & Sternberg, R. J. (2003) The nature–nurture issue. In: *An introduction to developmental psychology*, ed. A. Slater & G. Bremner, pp. 64–91. Blackwell. [RMF]
- Groenewegen, H. J. & Uylings, H. B. M. (2000) The prefrontal cortex and the integration of sensory, limbic, and autonomic information. In: *Progress in brain research, vol. 126, Cognition, emotion and autonomic responses: The integrative role of the prefrontal cortex and limbic structures*, ed. H. Uylings, C. Van Eden, J. De Bruin, M. Feenstra & C. Pennartz, pp. 3–28. Elsevier. [aCB]
- Gunnar, M. R. (2001) The role of glucocorticoids in anxiety disorders: A critical analysis. In: *The developmental psychopathology of anxiety*, ed. M. W. Vasey & M. R. Dadds, pp. 143–59. Oxford University Press. [OB]
- Gunnell, D., Harrison, G., Rasmussen, F., Fouskakis, D. & Tynelius, P. (2002) Associations between premorbid intellectual performance, early life exposures, and early onset schizophrenia. *British Journal of Psychiatry* 181:298–305. [aCB]
- Gustafsson, J.-E. (1984) A unifying model for the structure of intellectual abilities. *Intelligence* 8:179–203. [aCB, RPH, KK, MV]
- (1988) Hierarchical models of individual differences in cognitive abilities. In: *Advances in the psychology of human intelligence, vol. 4*, ed. R. Sternberg, pp. 35–71. Erlbaum. [aCB, KK]
- Haier, R. J. (1993) Cerebral glucose metabolism and intelligence. In: *Biological approaches to the study of human intelligence*, ed. P. A. Vernon. Ablex. [aCB]
- Haier, R. J., Jung, R. E., Yeo, R. A., Head, K. & Alkire, M. T. (2004) Structural brain variation and general intelligence. *NeuroImage* 23:425–33. [aCB]
- Haier, R. J., White, N. S. & Alkire, M. T. (2003) Individual differences in general intelligence correlate with brain function during nonreasoning tasks. *Intelligence* 31:429–41. [aCB]
- Halford, G. (1993) *Children's understanding: The development of mental models*. Erlbaum. [IVV]
- Halford, G. S., Baker, R., McCredden, J. E. & Bain, J. D. (2005) How many variables can humans process? *Psychological Science* 16:70–76. [NC]
- Hariri, A., Mattay, V. S., Tessitore, A., Fera, F. & Weinberger, D. R. (2003) Neocortical modulation of the amygdala response to fearful stimuli. *Biological Psychiatry* 53:494–501. [aCB]
- Haug, H., Barmwarter, U., Egger, R., Fischer, D., Kuhl, S. & Sass, N. L. (1983) Anatomical changes in the aging brain: Morphometric analysis of the human prosencephalon. In: *Aging, vol. 21: Brain aging: Neuropathology and neuropharmacology*, ed. J. Cervos-Navarro & H. I. Sarkander, pp. 1–12. Raven Press. [NAZ]
- Hedden, T. & Gabrieli, J. D. E. (2004) Insights into the aging mind: A view from cognitive neuroscience. *Nature Reviews: Neuroscience* 5:87–96. [rCB]
- Heinz, A., Braus, D. F., Smolka, M. N., Wrase, J., Puls, I., Hermann, D., Klein, S., Grusser, S. M., Flor, H., Schumann, G., Mann, K. & Buchel, C. (2005) Amygdala-prefrontal coupling depends on a genetic variation of the serotonin transporter. *Nature Neuroscience* 8:20–21. [MW]
- Heitz, R. P. & Engle, R. W. (submitted) Focusing the spotlight: Individual differences in visual attention control. [RPH]
- Heitz, R. P., Unsworth, N. & Engle, R. W. (2004) Working memory capacity, attention control, and fluid intelligence. In: *Handbook of understanding and measuring intelligence*, ed. O. Wilhelm and R. W. Engle. Sage. [RPH]
- Horn, J. L. (1970) Organization of data on life-span development of human abilities. In: *Life-span developmental psychology: Research and theory*, ed. L. R. Goulet and P. B. Baltes, p. 63. Academic Press. [NAZ]
- (1976) Human abilities: A review of research and theory in the early 1970s. *Annual Review of Psychology* 27:437–85.
- (1985) Remodeling old models of intelligence. In: *Handbook of intelligence: Theories, measurements, and applications*, ed. B. B. Wolman, pp. 267–300. Wiley. [WJ]
- (1989) Models of intelligence. In: *Intelligence: Measurement, theory, and public policy*, ed. R. L. Linn, pp. 29–73. University of Illinois Press. [WJ]
- (1998) A basis for research on age differences in cognitive capabilities. In: *Human cognitive abilities in theory and practice*, ed. J. J. McArdle & R. W. Woodcock, pp. 57–91. Riverside. [WJ]
- Horn, J. L. & Cattell, R. B. (1966) Refinement and test of the theory of fluid and crystallized intelligence. *Journal of Educational Psychology* 57:253–70. [JCK]
- (1967) Age differences in fluid and crystallized intelligence. *Acta Psychologica* 26:107–29. [aCB, KES, IVV]
- Horn, J. & Hofer, S. M. (1992) Major abilities and development in the adult period. In: *Intellectual development*, ed. R. Sternberg & C. Berg, pp. 44–91. Cambridge University Press. [aCB]
- Horn, J. & Noll, J. (1997) Human cognitive capabilities: Gf-Gc theory. In: *Contemporary intellectual assessment: Theories, tests and issues*, ed. D. Flanagan, J. Genshaft & P. Harrison, pp. 53–91. Guilford. [aCB, KES]
- Hummel, J. E. & Holyoak, K. J. (2003) A symbolic-connectionist theory of relational inference and generalization. *Psychological Review* 110:220–63. [IVV]
- Inhelder, B. & Piaget, J. (1958) *The growth of logical thinking from childhood to adolescence*. Basic Books. [JCK]
- Isingrini, M. & Vazou, F. (1997) Relation between fluid intelligence and frontal lobe in older adults. *International Journal of Aging and Human Development* 45:99–109. [NAZ]
- Jackendoff, R. (1996) How language helps us think. *Pragmatics and Cognition* 4:1–34. [KES]
- Jensen, A. R. (1998) *The g factor: The science of mental ability*. Praeger. [aCB, JRF, DG, WJ, MV]
- (2000a) “The g Factor” is about variance in mental abilities, not a cognitive theory of mental structure. *Psycoloquy*, 00.11.041.intelligence-g-factor.40.jensen. <http://ftp.princeton.edu/pub/harnad/Psycoloquy/2000.volume.11/>. [MA]
- (2000b) A nihilistic philosophy of science for a scientific psychology? *Psycoloquy*, 00.11.088.intelligence-g-factor.49.jensen. <http://ftp.princeton.edu/pub/harnad/Psycoloquy/2000.volume.11/>. [MA]
- Johnson, W. & Bouchard, J. T., Jr. (2005) The structure of human intelligence: It is verbal, perceptual, and image rotation (VPR), not fluid and crystallized. *Intelligence* 33:393–416. [rCB, WJ, MV]
- (in press) Constructive replication of the visual-perceptual-image rotation (VPR) model in Thurstone's (1941) battery of 60 tests of mental ability. *Intelligence*. [WJ]
- Johnson, W., Bouchard, J. T., Jr., Krueger, R. F., McGue, M. & Gottesman, I. I. (2004) Just one g: Consistent results from three test batteries. *Intelligence* 32:95–107. [WJ]
- Kail, R. (1991) Developmental change in speed of processing during childhood and adolescence. *Psychological Bulletin* 109:490–501. [RMF]
- Kane, M. J. & Engle, R. W. (2002) The role of prefrontal cortex in working memory capacity, executive attention, and general fluid intelligence: An individual-differences perspective. *Psychonomic Bulletin and Review* 9(4):637–71. [aCB, DG, RPH, NAZ]
- (2003) Working-memory capacity and the control of attention: The contributions of goal neglect, response competition, and task set to Stroop interference. *Journal of Experimental Psychology: General* 132(1):47–70. [KES]
- (2004) Working memory capacity and executive control of task-set switching. Paper presented at the 2nd International Conference on Working Memory, Kyoto, Japan, August 2004. [RPH]
- Kane, M. J., Bleckley, K. M., Conway, A. R. A. & Engle, R. W. (2001) A controlled-attention view of working-memory capacity. *Journal of Experimental Psychology: General* 130:169–83. [RPH]
- Kane, M. J., Hambrick, D. Z. & Conway, A. R. A. (2005) Working memory capacity and fluid intelligence are strongly related constructs: Comment on Ackerman, Beier, and Boyle (2005). *Psychological Bulletin* 131(1):66–71. [GCB, RPH]
- Kane, M. J., Hambrick, D. Z., Tuholski, S. W., Wilhelm, O., Payne, T. W. & Engle, R. W. (2004) The generality of working memory capacity: A latent variable approach to verbal and visuospatial memory span and reasoning. *Journal of Experimental Psychology: General* 133:189–217. [RPH]

- Kaufman, A. S. (2001) WAIS-III IQs, Horn's theory, and generational changes from young adulthood to old age. *Intelligence* 29:131–67. [JCK]
- Kaufman, A. S. & Kaufman, N. L. (1993) *Kaufman Adolescent and Adult Intelligence Test (KAIT) manual*. American Guidance Service. [JCK]
- (2004) *Kaufman Assessment Battery for Children*, 2nd edition. American Guidance Service. [JCK]
- Kaufman, J. & Charney, D. (2001) Effects of early stress on brain structure and function: Implications for understanding the relationship between child maltreatment and depression. *Development and Psychopathology* 13:451–71. [aCB]
- Keith, T. Z. (2005) Using confirmatory factor analysis to aid in understanding the constructs measured by intelligence tests. In: *Contemporary intellectual assessment: Theories, tests, and issues*, ed. D. P. Flanagan & P. L. Harrison, 2nd edition, pp. 581–614. Guilford Press. [JCK]
- Kinnunen, A. K., Keonig, J. I. & Bilbe, G. (2003) Repeated variable prenatal stress alters pre- and postsynaptic gene expression in the rat frontal pole. *Journal of Neurochemistry* 86:736–48. [aCB]
- Klingberg, T., Forsberg, H. & Westerberg, H. (2002) Training of working memory in children with ADHD. *Journal of Clinical and Experimental Neuropsychology* 24:781–91. [aCB]
- Koechlin, E., Basso, G., Pietrini, P., Panzer, S. & Grafman, J. (1999) The role of the anterior prefrontal cortex in human cognition. *Nature* 399:148–51. [aCB]
- Korkman, M., Kirk, U. & Kemp, S. (1998) *NEPSY: A developmental neuropsychological assessment*. Psychological Corporation. [JCK]
- Kremen, W. S., Seidman, L. J., Faraone, S. V. & Tsuang, M. T. (2001) Intelligence quotient and neuropsychological profile in patients with schizophrenia and in normal volunteers. *Biological Psychiatry* 50:453–62. [aCB]
- Krikorian, R. & Bartok, J. A. (1998) Developmental data for the Porteus Maze Test. *Clinical Neuropsychologist* 12:305–10. [aCB]
- Kuhn, T. S. (1962) *The structure of scientific revolutions*. University of Chicago Press. [rCB]
- Kyllonen, P. C. (1996) Is working memory capacity Spearman's g? In: *Human abilities: Their nature and measurement*, ed. I. Dennis & P. Tapsfield, pp. 49–76. Erlbaum. [aCB]
- Kyllonen, P. C. & Christal, R. E. (1990) Reasoning ability is (little more than) working memory capacity?! *Intelligence* 14:389–433. [DPB, aCB, DG, RPH]
- Laurent, J., Swerdluk, M. & Ryburn, M. (1992) Review of validity research on the Stanford-Binet Intelligence Scale: Fourth edition. *Psychological Assessment* 4:102–12. [aCB]
- Lautrey, J. (2002) Is there a general factor of cognitive development? In: *The general factor of intelligence: How general is it?* ed. E. L. Grigorenko & R. J. Sternberg, pp. 117–48. Erlbaum. [RMF]
- Le Pen, G., Gorttick, A. J., Higgins, G. A., Martin, J. R., Jenck, F. & Moreau, J.-L. (2000) Spatial and associative learning deficits induced by neonatal excitotoxic hippocampal damage in rats: Further evaluation of an animal model of schizophrenia. *Behavioral Pharmacology* 11:257–68. [aCB]
- LeDoux, J. E. (1989) Cognitive–emotional interactions in the brain. *Cognition and Emotion* 3:267–89. [aCB]
- (1995) Emotion: Clues from the brain. *Annual Review of Psychology* 46:209–35. [aCB]
- (1996) *The emotional brain*. Touchstone. [aCB]
- Lee, I. & Kessner, R. P. (2002) Differential contribution of NMDA receptors in hippocampal subregions to spatial working memory. *Nature Neuroscience* 5:162–68. [aCB]
- Lehrl, S., Triebig, G. & Fischer, B. (1995) Multiple-choice vocabulary test MWT as a valid and short test to estimate premorbid intelligence. *Acta Neurologica Scandinavica* 91:335–45. [MV]
- Leigland, L. A., Schulz, L. E. & Janowsky, J. S. (2004) Age related changes in emotional memory. *Neurobiology of Aging* 25:1117–24. [NAZ]
- Lépine, R., Barrouillet, P. & Camos, V. (2005) What makes working memory spans so predictive of high level cognition? *Psychonomic Bulletin and Review* 12:165–70. [NC]
- Leslie, A. M. (1987) Pretense and representation: The origins of “theory of mind.” *Psychological Review* 94:412–26. [KES]
- Lewis, D. A., Pierri, J. N., Volk, D. W., Melchitzky, D. S. & Woo, T. W. (1999) Altered GABA neurotransmission and prefrontal cortical dysfunction in schizophrenia. *Biological Psychiatry* 46:616–26. [aCB]
- Li, S.-C., Lindenberger, U., Hommel, B., Aschersleben, G., Prinz, W. & Baltes, P. (2004) Transformations in the couplings among intellectual abilities and constituent cognitive processes across the life span. *Psychological Science* 15:155–63.
- Lindley, S.E., Bengoechea, T.G., Wong, D.L., & Schatzberg, A.F. (2002) Mesotelencephalic dopamine neurochemical responses to glucocorticoid administration and adrenalectomy in Fischer 344 and Lewis rats. *Brain Research* 958: 414–22. [aCB]
- Lipska, B. K. & Weinberger, D. R. (2000a) Early disruption of corticolimbic circuitry as a model of schizophrenia. In: *Contemporary issues in modeling psychopathology*, ed. M. Myslobodsky & I. Weiner, pp. 259–74. Kluwer. [aCB]
- (2000b) To model a psychiatric disorder in animals: Schizophrenia as a reality test. *Neuropsychopharmacology* 23:223–39. [aCB]
- Lipska, B. K., Aultman, J. M., Verma, A., Weinberger, D. R. & Moghaddam, B. (2002a) Neonatal damage of the ventral hippocampus impairs memory in the rat. *Neuropsychopharmacology* 27:47–54. [aCB]
- Lipska, B.K., Halim, N.D., Segal, P.N. & Weinberger, D.R. (2002b) Effects of reversible inactivation of the neonatal ventral hippocampus on behavior in the adult rat. *Journal of Neuroscience* 22: 2835–42. [aCB]
- Liu, D., Diorio, J., Francis, D. D. & Meaney, M. J. (2000) Maternal care, hippocampal neurogenesis, and cognitive development in rats. *Nature Neuroscience* 3:799–806. [aCB]
- Logan, G. D. & Bundesen, C. (2003) Clever homunculus: Is there an endogenous act of control in the explicit task-cuing procedure? *Journal of Experimental Psychology: Human Perception and Performance* 29:575–99. [RPH]
- Lopez, J. F., Akil, H. & Watson, S. J. (1999) Neural circuits mediating stress. *Biological Psychiatry* 46:1461–71. [aCB]
- Lubinski, D. (2004) Introduction to the special section on cognitive abilities: 100 years after Spearman's 1904 “General intelligence,” objectively determined and measured.” *Journal of Personality and Social Psychology* 86:96–111. [WJ]
- Luciana, M. (2001) Dopamine-opiate modulations of reward-seeking behavior: Implications for the functional assessment of prefrontal development. In: *Handbook of developmental cognitive neuroscience*, ed. C. A. Nelson & M. Luciana. MIT Press. [OB]
- Luciana, M. & Nelson, C. A. (1998) The functional emergence of prefrontally-guided working memory systems in four- to eight-year-old children. *Neuropsychologia* 36:273–93. [aCB]
- Luciano, M., Wright, M. J., Geffen, G., Geffen, L., Smith, G. & Martin, N. (2004) A genetic investigation of the covariation among inspection time, choice reaction time, and IQ subtests. *Behavior Genetics* 34:41–50. [aCB]
- Luciano, M., Wright, M., Smith, G., Geffen, L. & Martin, N. (2001) Genetic covariance among measures of processing speed, working memory, and IQ. *Behavior Genetics* 31:581–92. [aCB]
- Luck, S. J. & Vogel, E. K. (1997) The capacity of visual working memory for features and conjunctions. *Nature* 390:279–81. [NC]
- Luria, A. R. (1970) The functional organization of the brain. *Scientific American* 222:66–78. [JCK]
- Lynn, R. (1990) The role of nutrition in secular increases in intelligence. *Personality and Individual Differences* 11:273–85. [MV]
- Maccari, S., Piazza, P. V., Kabbaj, M., Barbazanges, A., Simon, H. & Le Moal, M. (1995) Adoption reverses the long-term impairments in glucocorticoid feedback induced by prenatal stress. *Journal of Neuroscience* 15:110–16. [aCB]
- MacDonald, A. W., Cohen, J. D., Stegner, V. A. & Carter, C. S. (2000) Dissociating the role of dorsolateral prefrontal cortex and anterior cingulate cortex in cognitive control. *Science* 288:1835–38. [aCB]
- Mackintosh, N. J. (1998) *IQ and human intelligence*. Oxford University Press. [MV]
- Malkova, L., Bachevalier, J., Webster, M. & Mishkin, M. (2000) Effects of neonatal inferior prefrontal and medial temporal lesions on learning the rule for delayed nonmatching-to-sample. *Developmental Neuropsychology* 18(3):399–421. [aCB]
- Mathew, S. J., Shungu, D. C., Mao, X., Smith, E. L., Perera, G. M., Kegeles, L. S., Perera, T., Lisanby, S. H., Rosenblum, L. A., Gorman, J. M. & Coplan, J. D. (2003) A magnetic resonance spectroscopic imaging study of adult nonhuman primates exposed to early-life stressors. *Biological Psychiatry* 54:727–35. [OB]
- Mayberg, H. S., Liotti, M., Brannan, S. K., McGinnis, S., Mahurin, R. K., Jerabek, P. A., Silva, J. A., Tekell, J. L., Martin, C. C., Lancaster, J. L. & Fox, P. T. (1999) Reciprocal limbic-cortical function and negative mood: Converging PET findings in depression and normal sadness. *American Journal of Psychiatry* 156:675–82. [aCB]
- 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* 38:115–42. [aCB]
- McCandliss, B. D. & Noble, K. G. (2003) The development of reading impairment: A cognitive neuroscience model. *Mental Retardation and Developmental Disabilities Research Reviews* 9:196–205. [aCB]
- McGaugh, J. L., Cahill, L. & Roozendaal, B. (1996) Involvement of the amygdala in memory storage: Interaction with other brain systems. *Proceedings of the National Academy of Sciences USA* 93:13508–14.
- McGrew, K. S. (1997) Analysis of major intelligence batteries according to a proposed comprehensive gF-gC framework. In: *Contemporary intellectual assessment: Theories, tests and issues*, ed. D. Flanagan, J. Genshaft & P. Harrison, pp. 151–80. Guilford Press. [aCB, JCK]

## References/Blair: How similar are fluid cognition and general intelligence?

- 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. [aCB]
- McGrew, K. S. & Woodcock, R. W. (2001) *Technical manual: Woodcock-Johnson III*. Riverside. [KES]
- McLean, J. F. & Hitch, G. J. (1999) Working memory impairments in children with specific arithmetic learning difficulties. *Journal of Experimental Child Psychology* 74:240–60. [aCB]
- McLoyd, V. (1998) Socioeconomic disadvantage and child development. *American Psychologist* 53:185–204. [aCB]
- Meyer-Lindberg, A., Miletich, R. S., Kohn, P. D., Esposito, G., Carson, R. E., Quarantelli, M., Weinberger, D. R. & Berman, K. F. (2002) Reduced prefrontal activity predicts exaggerated striatal dopaminergic function in schizophrenia. *Nature Neuroscience* 5:267–71. [aCB]
- Miller, E. K. & Cohen, J. D. (2001) An integrative theory of prefrontal cortex function. *Annual Review of Neuroscience* 24:167–202. [aCB, GCB]
- Mingroni, M. A. (2004) The secular rise in IQ: Giving heterosis a closer look. *Intelligence* 32:65–83. [MV]
- Mink, J. W. (2003) The basal ganglia. In: *Fundamental neuroscience*, 2nd edition, ed. L. R. Squire, F. E. Bloom, S. K. McConnell, J. L. Roberts, N. C. Spitzer & M. J. Zigmond, pp. 815–39. Academic Press. [rCB]
- Miyake, A., Friedman, N. P., Emerson, M. J., Witzki, A. H., Howerter, A. & Wager, T. D. (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. [OB, arCB, GCB, RPH]
- Miyake, A., Friedman, N. P., Rettinger, D. A., Shah, P. & Hegarty, M. (2001) How are visuospatial working memory, executive functioning, and spatial abilities related? A latent-variable analysis. *Journal of Experimental Psychology: General* 130:621–40. [RPH]
- Morey, C. C. & Cowan, N. (2004) When visual and verbal memories compete: Evidence of cross-domain limits in working memory. *Psychonomic Bulletin and Review* 11:296–301.
- (2005) When do visual and verbal memories conflict? The importance of working-memory load and retrieval. *Journal of Experimental Psychology: Learning, Memory, and Cognition* 31(4):703–13. [NC]
- Morrison, R. G., Krawczyk, D. C., Holyoak, K. J., Hummel, J. E., Chow, T. W., Miller, B. L. & Knowlton, B. J. (2004) A neurocomputational model of analogical reasoning and its breakdown in Frontotemporal Lobar Degeneration. *Journal of Cognitive Neuroscience* 16:260–71. [IVV]
- Naglieri, J. A. & Das, J. P. (1997) *Cognitive assessment system interpretive manual*. Riverside. [JCK]
- Neisser, U., ed. (1998) *The rising curve: Long-term gains in IQ and related measures*. American Psychological Association. [MV]
- Neisser, U., Boodoo, G., Bouchard, T. J., Jr., Boykin, A. W., Brody, N., Ceci, S. J., Halpern, D. F., Loehlin, J. C., Perloff, R., Sternberg, R. J. & Urbina, S. (1996) Intelligence: Knowns and unknowns. *American Psychologist* 51:77–101. [DG]
- Nesse, R. (1998) Emotional disorders in evolutionary perspective. *British Journal of Medical Psychology* 71:397–415. [EST]
- Nichols, S. & Stich, S. P. (2003) *Mindreading: An integrated account of pretence, self-awareness, and understanding other minds*. Oxford University Press. [KES]
- Noble, K. G., Norman, M. F. & Farrah, M. J. (2005) Neurocognitive correlates of socioeconomic status in kindergarten children. *Developmental Science* 8:74–87. [RMF]
- Oberauer, K. (2002) Access to information in working memory: Exploring the focus of attention. *Journal of Experimental Psychology: Learning, Memory, and Cognition* 28:411–21. [NC]
- Oberauer, K., Süß, H., Wilhelm, O. & Wittman, W. W. (2003) The multiple faces of working memory: Storage, processing, supervision, and coordination. *Intelligence* 31:167–93. [RPH]
- 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* 14:1215–29. [aCB]
- O'Connor, T. G., Bredenkamp, D., Rutter, M. & the English and Romanian Adoptees (ERA) Study Team (1999) Attachment disturbances and disorders in children exposed to early severe deprivation. *Infant Mental Health Journal* (Special Issue: *Disturbances and Disorders of Attachment*) 20:10–29. [OB]
- Olesen, P., Westerberg, H. & Klingberg, T. (2004) Increased prefrontal and parietal activity after training of working memory. *Nature Neuroscience* 7:75–79. [rCB]
- Panksepp, J. (2003) Can anthropomorphic analyses of separation cries in other animals inform us about the emotional nature of social loss in humans? Comment on Blumberg and Sokoloff (2001). *Psychological Review* 110:376–88. [OB]
- Paus, T. (2001) Primate anterior cingulate cortex: Where motor control, drive, and cognition interface. *Nature Reviews: Neuroscience* 2:417–24. [aCB]
- Pennington, B. F. (1997) Dimensions of executive functions in normal and abnormal development. In: *Development of the prefrontal cortex: Evolution, neurobiology, and behavior*, ed. N. Krasnegor, R. Lyon & P. Goldman-Rakic, pp. 265–81. Brookes. [aCB]
- Pennington, B. F. & Ozonoff, S. (1996) Executive functions and developmental psychopathology. *Journal of Child Psychology and Psychiatry* 37:51–87. [aCB]
- Peterson, S. E., van Mier, H., Fiez, J. A. & Raichle, M. E. (1998) The effects of practice on the functional anatomy of task performance. *Proceedings of the National Academy of Sciences USA* 95:853–60. [GCB]
- Plomin, R. & Craig, I. W. (in press) Intelligence. *Annual Review of Genomics and Human Genetics*. [WJ]
- Plomin, R. & Spinath, F. (2002) Genetics and general cognitive ability (g). *Trends in Cognitive Sciences* 6:169–76. [aCB]
- Posner, M. I. & Peterson, S. E. (1990) The attention system of the human brain. *Annual Review of Neuroscience* 13:25–42. [NC]
- Posner, M. I. & Rothbart, M. K. (1998) Attention, self regulation and consciousness. *Philosophical Transactions of the Royal Society of London* 353:1915–27. [OB]
- (2000) Developing mechanisms of self-regulation. *Development and Psychopathology* 12:427–41. [OB, arCB]
- (2004) Developing self-regulation in preschool children. Paper presented at the annual meeting of the American Association for the Advancement of Science, Seattle, Washington, February 2004. [aCB]
- Postle, B. R., Berger, J. S. & D'Esposito, M. (1999) Functional neuroanatomical double dissociation of mnemonic and executive control processes contributing to working memory performance. *Proceedings of the National Academy of Sciences USA* 96:12959–64. [NC]
- Postle, B. R., Druzgal, T. J. & D'Esposito, M. (2003) Seeking the neural substrates of visual working memory storage. *Cortex* 39:927–46.
- Povinelli, D. J. & Giambone, S. (2001) Reasoning about beliefs: A human specialization? *Child Development* 72:691–95. [KES]
- 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. [aCB]
- Prabhakaran, V., Rypma, B. & Gabrieli, J. D. E. (2001) Neural substrates of mathematical reasoning: A functional magnetic resonance imaging study of neocortical activation during performance of the Necessary Arithmetic Operations Test. *Neuropsychology* 15:115–27. [aCB]
- Prabhakaran, V., Smith, J. A. L., Desmond, J. E., Glover, G. H. & Gabrieli, J. D. E. (1997) Neural substrates of fluid reasoning: An fMRI study of neocortical activation during performance of the Raven's Progressive Matrices Test. *Cognitive Psychology* 33:43–63. [aCB, DG]
- Pugh, K., Mencl, W., Jenner, A., Katz, L., Frost, S., Lee, J., Shaywitz, S. & Shaywitz, B. (2001) Neurobiological studies of reading and reading disability. *Journal of Communication Disorders* 34:479–92. [aCB]
- Puglisi-Allegra, S., Cabib, S., Pascucci, T., Ventura, R., Cali, F. & Romano, V. (2000) Dramatic brain aminergic deficit in a genetic mouse model of phenylketonuria. *NeuroReport* 11:1361–64. [aCB]
- Ramey, C. T. & Campbell, F. A. (1991) Poverty, early childhood education, and academic competence: The Abecedarian experiment. In: *Children in poverty*, ed. A. Huston. Cambridge University Press. [aCB]
- Ramey, C. T., Campbell, F. A. & Blair, C. (1998) The Abecedarian Project: Long-term effectiveness of educational daycare beginning at birth. In: *Social programs that work*, ed. J. Crane, pp. 163–83. Russell Sage Foundation. [aCB]
- Ranganath, C., Johnson, M. K. & D'Esposito, M. (2003) Prefrontal activity associated with working memory and episodic long-term memory. *Neuropsychologia* 41:378–89. [aCB]
- Rapoport, M., van Reekum, R. & Mayberg, H. (2000) The role of the cerebellum in cognition and behavior: A selective review. *Journal of Neuropsychiatry and Clinical Neurosciences* 12:193–98. [MW]
- Raz, N. (1996) Neuroanatomy of the aging brain observed in vivo. In: *Neuroimaging II: Clinical applications*, pp. 153–82, ed. E. D. Bigler. Plenum Press. [NAZ]
- Raz, N., Torres, I. J., Spencer, W. D. & Acker, J. D. (1993) Pathoclysis in aging human cerebral cortex: Evidence from in vivo MRI morphometry. *Psychobiology* 15:21–36. [NAZ]
- Richland, L. E., Morrison, R. G. & Holyoak, K. J. (2004) Working memory and inhibition as constraints on children's development of analogical reasoning. In: *Proceedings of the Twenty-sixth Annual Conference of the Cognitive Science Society*, ed. K. Forbus, D. Gentner & T. Regier, pp. 1149–54. Erlbaum. [IVV]
- Robin, N. & Holyoak, K. J. (1995) Relational complexity and the functions of prefrontal cortex. In: *The cognitive neurosciences*, ed. M. S. Gazzaniga, pp. 987–97. MIT Press. [IVV]
- Roid, G. H. (2003) *Stanford-Binet intelligence scales*, 5th edition. Riverside. [JCK]

- Roozendaal, B. (2000) Glucocorticoids and the regulation of memory. *Psychoneuroendocrinology* 25:213–38. [aCB]
- Rowe, D., Jacobsen, K. & Van den Oord, E. (1999) Genetic and environmental influences on vocabulary IQ: Parental education level as moderator. *Child Development* 70:1151–62. [aCB]
- Rushton, J. P. (1999) Secular gains in IQ not related to the g factor and inbreeding depression – unlike Black–White differences: A reply to Flynn. *Personality and Individual Differences* 26:381–89. [MV]
- Russell, J. (1999) Cognitive development as an executive process – in part: A homeopathic dose of Piaget. *Developmental Science* 2:247–95. [RMF]
- Rypma, B., Prabhakaran, V., Desmond, J. E., Glover, G. H. & Gabrieli, J. D. E. (1999) Load dependent roles of frontal brain regions in the maintenance of working memory. *NeuroImage* 9:216–26. [aCB]
- Salthouse, T. A., Atkinson, T. M. & Berish, D. E. (2003) Executive functioning as a potential mediator of age-related cognitive decline in normal adults. *Journal of Experimental Psychology: General* 132:566–94. [KES]
- Saunders, R. C., Kolachana, B. S., Bachevalier, J. & Weinberger, D. R. (1998) Neonatal lesions of the medial temporal lobe disrupt prefrontal cortical regulation of striatal dopamine. *Nature* 393:169–71. [aCB]
- Sawaguchi, T. & Goldman-Rakic, P. S. (1991) D1 dopamine receptors in prefrontal cortex: Involvement in working memory. *Science* 251:947–50. [aCB]
- Schacter, D. L. (1989) On the relation between memory and consciousness: Dissociable interactions and conscious experience. In: *Varieties of memory and consciousness: Essays in honor of Endel Tulving*, ed. H. L. Roediger & F. I. M. Craik. Erlbaum. [NC]
- Schaie, K. W. (1994) The course of adult intellectual development. *American Psychologist* 49:304–13. [aCB]
- Schallberger, U. (1987) HAWIK und HAWIK-R: Ein empirischer Vergleich [HAWIK and HAWIK-R: An empirical comparison]. *Diagnostica* 33:1–13. [MV]
- Schmahmann, J. D. (1998) Dysmetria of thought: Clinical consequences of cerebellar dysfunction on cognition and affect. *Trends in Cognitive Sciences* 2:362–71. [aCB]
- Schretlen, D., Pearlson, G. D., Anthony, J. C., Aylward, E. H., Augustine, A. M., Davis, A. & Barta, P. (2000) Elucidating the contributions of processing speed, executive ability and frontal lobe volume to normal age-related differences in fluid intelligence. *Journal of the International Neuropsychological Society* 6:52–61. [NAZ]
- Schubert, M. T. & Berlach, G. (1982) Neue Richtlinien zur Interpretation des Hamburg-Wechsler-Intelligenztests für Kinder (HAWIK) [New guidelines for the interpretation of the Hamburg-Wechsler Intelligence Test for Children (HAWIK)]. *Zeitschrift für Klinische Psychologie* 11:253–79. [MV]
- Schultz, S. K. & Andreasen, N. C. (1999) Schizophrenia. *Lancet* 353:1425–30. [MW]
- Seamans, J. K., Floresco, S. B. & Philips, A. G. (1998) D1 receptor modulation of hippocampal-prefrontal cortical circuits integrating spatial memory with executive functions in the rat. *Journal of Neuroscience* 18:1613–21. [aCB]
- Shaywitz, B., Shaywitz, S., Pugh, K., Mencl, W., Fulbright, K., Skudlarski, P., Constable, R., Marchione, K., Fletcher, J., Lyon, G. R. & Core, J. (2002) Disruption of posterior brain systems for reading in children with developmental dyslexia. *Biological Psychiatry* 52:101–10. [aCB]
- Siegler, R. (1996) *Emerging minds: The process of change in children's thinking*. Oxford University Press. [RMF]
- Sikora, D. M., Haley, P., Edwards, J. & Butler, R. W. (2002) Tower of London performance in children with poor arithmetic skills. *Developmental Neuropsychology* 21:243–54. [aCB]
- Simon, J. R. & Berbaum, K. (1990) Effect of conflicting cues on information processing: The “Stroop effect” vs. the “Simon effect.” *Acta Psychologica (Amsterdam)* 73:159–70. [OB]
- Simon, O., Kherif, F., Flandin, G., Poline, J., Riviere, D., Mangin, J., Le Bihan, D. & Dehaene, S. (2004) Automated clustering and functional geometry of human parietofrontal networks for language, space, and number. *Neuroimage* 23:1192–202. [rCB]
- Smith, E. E. & Jonides, J. (1997) Working memory: A view from neuroimaging. *Cognitive Psychology* 33:5–42. [aCB]
- (1999) Storage and executive processes in the frontal lobes. *Science* 283:1657–61. [rCB, GCB]
- Smith, E. E., Jonides, J. & Koeppel, R. A. (1996) Dissociating verbal and spatial working memory using PET. *Cerebral Cortex* 6:11–20. [aCB]
- Snyderman, M. & Rothman, S. (1987) Survey of expert opinion on intelligence and aptitude testing. *American Psychologist* 42:137–44. [DG]
- Spearman, C. (1927) *The abilities of man: Their nature and measurement*. Macmillan. [aCB]
- Sperber, D. (2000) Metarepresentations in evolutionary perspective. In: *Metarepresentations: A multidisciplinary perspective*, ed. D. Sperber, pp. 117–37. Oxford University Press. [KES]
- Stanovich, K. E. (2004) *The robot's rebellion: Finding meaning in the age of Darwin*. University of Chicago Press. [KES]
- Stanovich, K. E., Siegel, L. S. & Gottardo, A. (1997) Converging evidence for phonological and surface subtypes of reading disability. *Journal of Educational Psychology* 89:114–27. [aCB]
- Steels, L. & Belpaeme, T. (2005) Coordinating perceptually grounded categories through language. A case study for colour. *Behavioral and Brain Sciences* 28(6):469–89. [EST]
- Sternberg, R. J. (1996) *Successful intelligence: How practical and creative intelligence determine success in life*. Simon and Schuster. [aCB]
- (2002) Individual differences in cognitive development. In: *Blackwell handbook of childhood cognitive development*, ed. U. Goswami, pp. 600–19. Blackwell. [RMF]
- Sternberg, R. & Grigorenko, E., eds. (2002) *The general factor of intelligence: How general is it?* Erlbaum. [aCB]
- Sternberg, R. J., Grigorenko, E. L., Ngorosho, D., Tantufuye, E., Mbise, A., Nokes, C., Jukes, M. & Bundy, D. A. (2002) Assessing intellectual potential in rural Tanzanian school children. *Intelligence* 30:141–62. [aCB]
- Stevanovski, B. & Jolicoeur, P. (2003) Attentional limitations in visual short-term memory. Poster presented at the annual convention of the Psychonomic Society, Vancouver, British Columbia, Canada, November 2003. [NC]
- Storfer, M. D. (1990) *Intelligence and giftedness: The contributions of heredity and early environment*. Jossey-Bass. [MV]
- Stuss, D. T. & Alexander, M. P. (2005) Does damage to the frontal lobes produce impairment in memory? *Current Directions in Psychological Science* 14:84–88. [rCB]
- Sullivan, R. M. & Gratton, A. (2002) Prefrontal cortical regulation of hypothalamic-pituitary-adrenal function in the rat and implications for psychopathology: Side matters. *Psychoneuroendocrinology* 27:99–114. [aCB]
- Sundet, J. M., Barlaug, D. G. & Turjussen, T. M. (2004) The end of the Flynn effect? A study of secular trends in mean intelligence test scores of Norwegian conscripts during half a century. *Intelligence* 32:349–62. [MV]
- Stüb, H. M., Oberauer, K., Wittman, W., Wilhelm, O. & Schulz, R. (2002) Working memory capacity explains reasoning ability – and a little bit more. *Intelligence* 30:261–88. [aCB]
- Sutton, S. K. & Davidson, R. J. (1997) Prefrontal brain asymmetry: A biological substrate of the behavioral approach and behavioral inhibition systems. *Psychological Science* 8:204–10. [aCB]
- Swanson, H. L. (1999) Reading comprehension and working memory in learning-disabled readers: Is the phonological loop more important than the executive system? *Journal of Experimental Child Psychology* 72:1–31. [aCB]
- 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. [aCB]
- Sylvester, C., Wager, T., Lacey, S., Hernandez, L., Nichols, T., Smith, E. & Jonides, J. (2003) Switching attention and resolving interference: fMRI measures of executive functions. *Neuropsychologia* 41:357–70. [aCB]
- Teasdale, T. W. & Owen, D. R. (in press) A long-term rise and recent decline in intelligence test performance: The Flynn Effect in reverse. *Personality and Individual Differences*. [MV]
- 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. [aCB]
- Thompson, P., Cannon, T., Narr, K., van Erp, T., Poutanen, V., Huttunen, M., Lonnqvist, J., Standertskjöld-Nordenstam, C., Kaprio, J., Khaledy, M., Dail, R., Zoumalan, C. & Toga, A. (2001) Genetic influences on brain structure. *Nature Neuroscience* 4:1253–58. [aCB]
- Todd, J. J. & Marois, R. (2004) Capacity limit of visual short-term memory in human posterior parietal cortex. *Nature* 428:751–54. [NC]
- Toga, A. W. & Thompson, P. M. (2005) Genetics of brain structure and intelligence. *Annual Review of Neuroscience* 28:1–23. [rCB]
- Tomasello, M. (1999) *The cultural origins of human cognition*. Harvard University Press. [KES]
- Turkheimer, E., Haley, A., Waldron, M., D’Onofrio, B. & Gottesman, I. (2003) Socioeconomic status modifies heritability of IQ in young children. *Psychological Science* 14:623–28. [aCB]
- Unsworth, N. & Engle, R. W. (2005) Working memory capacity and fluid abilities: Examining the correlation between operation span and Raven. *Intelligence* 33:67–81. [DG]
- Unsworth, N., Schrock, J. C. & Engle, R. W. (2004) Working memory capacity and the antisaccade task: Individual differences in voluntary saccade control. *Journal of Experimental Psychology: Learning, Memory, and Cognition* 30:1302–21. [RPH]
- Uylings, H., Van Eden, C., De Bruin, J., Feenstra, M. & Pennartz, C., eds. (2000) *Progress in brain research, vol. 126: Cognition, emotion and autonomic*

- responses: *The integrative role of the prefrontal cortex and limbic structures*. Elsevier. [aCB]
- Van Eden, C. G. & Buijs, R. M. (2000) Functional neuroanatomy of the prefrontal cortex: Autonomic interactions. In: *Progress in brain research, vol. 126, Cognition, emotion and autonomic responses: The integrative role of the prefrontal cortex and limbic structures*, ed. H. Uylings, C. Van Eden, J. De Bruin, M. Feenstra & C. Pennartz, pp. 49–62. Elsevier. [aCB]
- Van der Werf, Y., Scheltens, P., Lindeboom, J., Witter, M., Uylings, H. & Jolles, J. (2003) Deficits of memory, executive functioning and attention following infarction in the thalamus: A study of 22 cases with localised lesions. *Neuropsychologia* 41:1330–44. [aCB]
- Van der Werf, Y., Witter, M., Uylings, H. & Jolles, J. (2000) Neuropsychology of infarctions in the thalamus: A review. *Neuropsychologia* 38:613–27. [aCB]
- Varela, F. J., Thompson, E. & Rosch, E. (1991) *The embodied mind, cognitive science and human experience*. MIT Press. [EST]
- Vazquez, D. M. (1998) Stress and the developing limbic-hypothalamic-pituitary-adrenal axis. *Psychoneuroendocrinology* 23:663–700. [aCB]
- Vernon, P. (1964) *The structure of human abilities*. Methuen. [WJ]
- (1965) Ability factors and environmental influences. *American Psychologist* 20:723–33. [rCB, WJ]
- Viskontas, I. V., Holyoak, K. J. & Knowlton, B. J. (in press) Integrating multiple relations: Working memory capacity constrains reasoning ability in older adults. *Thinking and Reasoning*. [IVV]
- Viskontas, I. V., Morrison, R. G., Holyoak, K. J., Hummel, J. E. & Knowlton, B. J. (2004) Relational integration, inhibition and analogical reasoning in older adults. *Psychology and Aging* 19:581–91. [IVV]
- Vogel, E. K. & Machizawa, M. G. (2004) Neural activity predicts individual differences in visual working memory capacity. *Nature* 428:749–51. [NC]
- Voracek, M. (2002) Drei Studien zum Mehrfachwahl-Wortschatz-Intelligenztest (MWT): Test-Reanalyse, Lynn-Flynn-Effekt, und Phase-IV-Studie [Three studies on the multiple-choice vocabulary test (MWT): Test reanalysis, Lynn-Flynn effect, and Phase-IV study]. Unpublished doctoral dissertation, University of Vienna. [MV]
- Vygotsky, L. S. (1978) *Mind in society: The development of higher psychological processes*. Harvard University Press. [RMF]
- Wahlsten, D. (1996) The intelligence of heritability. *Canadian Psychology* 35:244–58. [rCB]
- (1997) The malleability of intelligence is not constrained by heritability. In: *Intelligence, genes and success*, ed. B. Devlin, S. Feinberg, D. Resnick & K. Roeder, pp. 71–87. Springer-Verlag. [aCB]
- Waltz, J. A., Knowlton, B. J., Holyoak, K. J., Boone, K. B., Back-Madruga, C., McPherson, S., Masterman, D., Chow, T., Cummings, J. L. & Miller, B. L. (2004) Relational integration and executive function in Alzheimer's disease. *Neuropsychology* 18:296–305. [IVV]
- 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 relational reasoning in the human prefrontal cortex. *Psychological Science* 10:119–25. [aCB, NC, IVV]
- Weaver, I. C. G., Cervoni, N., Champagne, F. A., D'Alessio, A. C., Sharma, S., Seckl, J. R., Dymov, S., Szyf, M. & Meaney, M. J. (2004) Epigenetic programming by maternal behavior. *Nature Neuroscience* 7:847–54. [WJ]
- Wechsler, D. (1997) *WAIS-III administration and scoring manual*. Psychological Corporation. [JCK]
- (2002) *The Wechsler Preschool and Primary Scale of Intelligence*, 3rd edition. Psychological Corporation. [JCK]
- (2003) *The Wechsler Intelligence Scale for Children*, 4th edition. Psychological Corporation. [JCK]
- 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* 149:890–97. [aCB]
- Weinberger, D. R., Egan, M. F., Bertolino, A., Callicott, J. H., Mattay, V. S., Lipska, B. K., Berman, K. F. & Goldberg, T. E. (2001) Prefrontal neurons and the genetics of schizophrenia. *Biological Psychiatry* 50:825–44. [aCB]
- Weiser, M., Noy, S., Kaplan, Z., Reichenberg, A., Yasvitsky, R., Nahon, D., Grotto, I. & Knobler, H. (2003) Generalized cognitive impairment in male adolescents with schizotypal personality disorder. *American Journal of Medical Genetics* 116B:36–40. [aCB]
- Welsh, M. C. & Pennington, B. F. (1988) Assessing frontal lobe functioning in children: Views from developmental psychology. *Developmental Neuropsychology* 4:199–230. [aCB]
- Welsh, M. C., Pennington, B. F. & Grosser, D. B. (1991) A normative developmental study of executive function: A window on prefrontal function in children. *Developmental Neuropsychology* 7:131–49. [aCB]
- Welsh, M. C., Pennington, B. F., Ozonoff, S., Rouse, B. & McCabe, E. R. B. (1990) Neuropsychology of early treated phenylketonuria: Specific executive function deficits. *Child Development* 61:1697–713. [aCB]
- West, R. L. (1996) An application of prefrontal cortex function theory to cognitive aging. *Psychological Bulletin* 120:272–92. [aCB]
- Whalen, P. J. (1998) Fear, vigilance, and ambiguity: Initial neuroimaging studies of the human amygdala. *Current Directions in Psychological Science* 7:177–88. [aCB]
- Whimby, A. E. & Dennenberg, V. H. (1967) Experimental programming of life histories: The factor structure underlying experimentally created individual differences. *Behaviour* 29:296–314. [aCB]
- Whitehead, A. N. (1925/1948) *Science and the modern world*. Macmillan. [rCB]
- Wicherts, J., Dolan, C., Hessen, D., Oosterveld, P., van Baal, C., Boomsma, D. & Span, M. (2004) Are intelligence tests measurement invariant over time? Investigating the nature of the Flynn effect. *Intelligence* 32:509–37. [aCB, JRF]
- Wilke, M., Sohn, J. H., Weber Byars, A. M. & Holland, S. K. (2003) Bright spots: Correlations of gray matter volume with IQ in a normal pediatric population. *NeuroImage* 20:202–15. [aCB, MW]
- 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* 110:157–72. [aCB]
- Williams, W. M. (1998) Are we raising smarter children today? School- and home-related influences on IQ. In: *The rising curve: Long term gains in IQ and related measures*, ed. U. Neisser, pp. 125–54. American Psychological Association. [aCB]
- Woodcock, R. W. (1990) Theoretical foundations of the WJ-R measures of cognitive ability. *Journal of Psychoeducational Assessment* 8:231–58. [aCB, JCK]
- Woodcock, R. W., McGrew, K. S. & Mather, N. (2001) *Woodcock-Johnson III*. Riverside. [JCK]
- Wytek, R., Opgenoorth, E. & Presslich, O. (1984) Development of a new shortened version of Raven's matrices test for application and rough assessment of present intellectual capacity within psychopathological investigation. *Psychopathology* 17:49–58. [MV]
- Yang, C. R., Seamans, J. K. & Gorelova, N. (1999) Developing a neuronal model of the pathophysiology of schizophrenia based on the nature of electrophysiological actions of dopamine in the prefrontal cortex. *Neuropsychopharmacology* 21:161–94. [aCB]
- Zelazo, P. D. (2004) The development of conscious control in childhood. *Trends in Cognitive Sciences* 8:12–17. [RMF]
- Zelazo, P. D., Qu, L. & Müller, U. (2005) Hot and cool aspects of executive function: Relations in early development. In: *Young children's cognitive development: Interrelationships among executive functioning, working memory, verbal ability, and theory of mind*, ed. W. Schneider, R. Schumann-Hengsteler & B. Sodian, pp. 71–93. Erlbaum. [RMF]
- Zigler, E. (1999) The individual with mental retardation as a whole person. In: *Personality development in individuals with mental retardation*, ed. E. Zigler & D. Bennett-Gates, pp. 1–16. Cambridge University Press. [aCB]
- Zigler, E., Abelson, W. D. & Seitz, V. (1973) Motivational factors in the performance of economically disadvantaged children on the Peabody Picture Vocabulary Test. *Child Development* 44:294–303. [aCB]
- Zook, N., Welsh, M. & Ewing, V. (in press) Performance of healthy, older adults on the Tower of London – Revised: Comparisons with the WAIS-III Vocabulary and Matrix Reasoning Subtests. *Journal of Aging, Neuropsychology and Cognition*. [rCB, NAZ]