

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.

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

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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

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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