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

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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

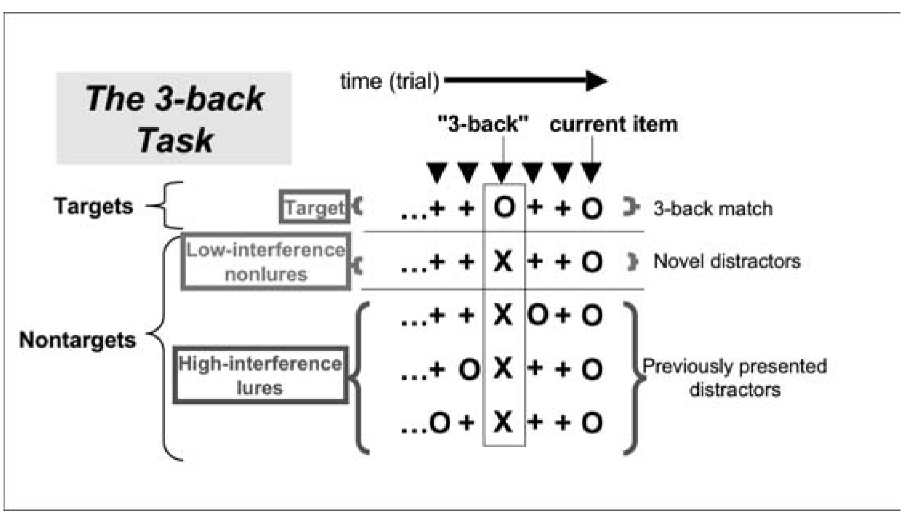

Figure 1 (Burgess et al.). The 3-back working memory (WM) task. A sequential series of items are presented, and judgments are made regarding whether the currently presented item (the *O*) matches the item presented three trials back (*targets*, first row). The task is thought to tap not only into the 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.

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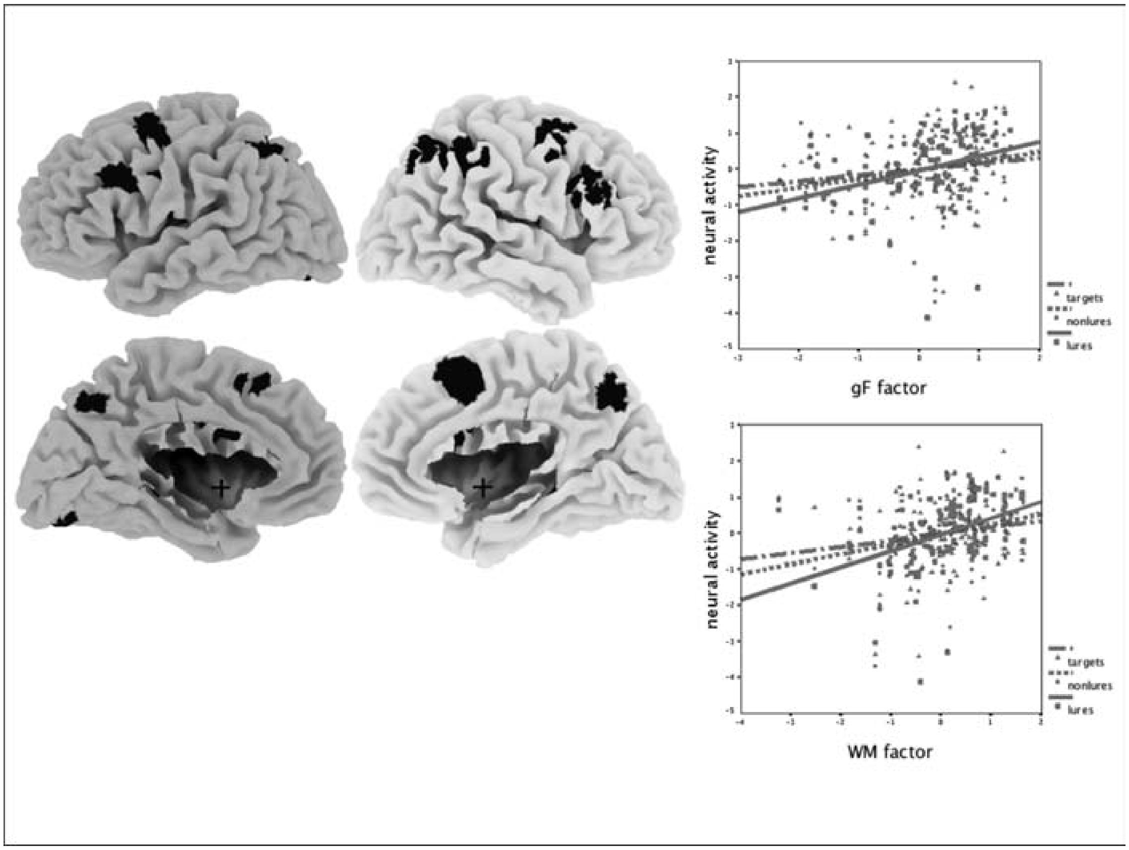

Figure 2 (Burgess et al.). Correlations between neural activity in executive function (EF)–related brain regions and fluid intelligence (gF) and working memory (WM) span. By experimentally manipulating the presence of interference across trial types, we could index the relationships between gF (or WM 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.

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Within fluid cognition: Fluid processing and fluid storage?

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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

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