High abilities at fluid analogizing: a cognitive neuroscience construct of giftedness

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For many educators in the field of gifted education, the most endearing characteristic of gifted children is their creative intelligence: their capacity for original explanations, insightful questions, elegant proofs, original creations, and quirky humor. Such a basket of cognitive behaviors begs the question of an underlying cognitive generator and, hence, some delineating neural correlates (Kalbfleisch, 2004). Here it is proposed that gifted intelligence is an outcome of an enhanced facility to engage in fluid analogizing--a cognitive-level construct that describes selective intermodule information processing within the brain (Dehaene, Kerszberg, & Changeux, 1998). Fluid analogizing supports a suite of neural functions associated with working memory (Geake & Hansen, 2005). Consequently, a gifted person's high ability at fluid analogizing explains their more efficacious working memory, which in turn supports high levels of creative intelligence (Geake, in press).

Thus, the aim of this article is to present a case for fluid analogizing as a useful construct with which to better understand giftedness. The adequacy of the neural underpinnings of this argument could be judged in the light of two recent extensive reviews of the considerable literature concerning the neural correlates of general intelligence, in particular, the interactive involvement of the frontal and parietal areas (Jung & Haier, 2007), and the neural correlates of high-level fluid reasoning, including an explanation of the Flynn Effect of rising IQ scores (Blair, 2006). It is not the purpose of this article to review these extensive reviews: they are recommended reading for anyone interested in this area of research.

However, in an attempt to illustrate the utility of a fluid analogizing construct of giftedness, the article concludes with a post hoc (and therefore possibly somewhat conjectural) consideration of some earlier research on the information processing characteristics of musical prodigies.

FLUID ANALOGIZING AS A FUNDAMENTAL COGNITIVE PROCESS

Historically, the most enduring conceptualization of human intelligence is that it is essentially analogical. As William James (1895) wrote over a century ago: "A native talent for perceiving analogies is ... the leading fact in genius of every order" (p. 530). That is, the essence of intelligent behavior lies in making insightful metaphors or analogies (Dunbar, 2001; French, 2002; Goswami, 2001; Halford, 1992; Holyoak & Thagard, 1995). Evidence that this is a fundamental cognitive process comes from studies of the conceptual development of young children, which is characteristically analogical (Goswami, 2001). Insightful analogy making is necessary for success in a wide range of endeavors, including pattern recognition, composition of musical variations, producing and appreciating humor, translation between languages, poetry, classroom exercises, and much of everyday speech (Goswami, 2001;

Holyoak & Thagard, 1995). In education, a characteristic of good teachers is their ability to create analogies for explanation and clarification (Geake, 2003).

While making an analogy is clearly rooted in perceptual experience, it goes beyond perception in employing relationships (Mitchell, 1993). Moreover, such relationships rarely involve analogical exactness, as in the classic "White is to black as day is to ...?" For real-world higher order categorical relationships, Hofstadter (2001) argues that: "Categories are quintessentially fluid entities; they adapt to a set of incoming stimuli and try to align themselves with it. The process of inexact matching between prior categories and new things being perceived ... is analogy-making par excellence" (p. 499). That is, analogizing as a basic cognitive process is not exact analogizing, but fluid analogizing. In contrast to an exact analogy question where there is one correct response, in a fluid analogy there may be a range of responses, some more plausible or creative than others. For example, to the question: "What is the London of the United States?" plausible responses include "Washington, DC, because it is the capital; New York because it is the largest city; Los Angeles because it is the center of the national film industry," and so on. Importantly, none of these responses are wrong but rather highlight the multidimensional possibilities of categorization. Consequently, it is the judicious (albeit often instinctive) employment of fluid rather than exact analogies that constitutes effective pedagogy enabling efficient categorization and assimilation of new knowledge (Geake & Dobson, 2005). Of relevance here, a notable characteristic of gifted children's metacognitive explanations is their recourse to fluid analogizing (Clark, 1997).

As a pioneering formalization of fluid analogizing, the AI program, Copycat, constructed by Melanie Mitchell and Douglas Hofstadter, sought fluid applications of a implicit transformation rule that was applied to a pair of letter strings (Hofstadter, 1995; Mitchell, 1993). The only internal knowledge required of the program was alphabetical and reverse-alphabetical order, and the boundary conditions of the English alphabet, the letters "a" and "z." The task, given the first transformation pair, was to complete the second in an analogous way. As a simple example, to abc [right arrow] abd, ijk [right arrow] ? most people respond "ijl" (increase the last letter by one), although "ijd" (change the last letter to "d") and other responses are possible. Copycat responded similarly. However, examples can be made arbitrarily more complex, such as abc [right arrow] abd, iijjkk [right arrow] ? or a [right arrow] ab, z [right arrow] ? each of which have a number of plausible responses. The various responses can be analyzed in terms of the number of transformations required to construct it and quantified as a metric: the analogical depth response (ADR; Geake & Hansen, 2005).

For example, in the example abc [right arrow] abd, pqqrrr [right arrow] ?, plausible responses could include:

1. pqqrrr (ADR = 1: new letter sequence);

2. pqqrrd (ADR = 2: new letter sequence, last letter copy);

3. pqqrrs (ADR = 3: new letter sequence, alphabet preservation, letter advance);

4. pqqsss (ADR = 4: new letter sequence, alphabet preservation, grouping, letter advance);

5. pqqssss (ADR = 5: new letter sequence, alphabet preservation, grouping, numerical increase, letter advance).

Consequently, one would expect presentation of fluid analogies to humans (in contrast to an AI computer program such as Copycat) to elicit considerable variance in plausible responses. This was demonstrated by Burns (1996) using the Hofstadter/Mitchell letter string fluid analogies (Mitchell, 1993), where among 74 respondents abc => abd, kji => ? received 12 different responses (kjh, kjj, lji, etc.), and abc => abd, mrrjjj => ? received 20 different responses (mrrkkk, mrrjjk, mrsjjk, jjmrr, etc.). Such variance in human fluid analogizing suggested that these letter strings could serve as suitable stimuli for neuroimaging investigations into the neural correlates of fluid analogizing.

THE NEUROBIOLOGY OF FLUID ANALOGIZING

If, as has been argued above, fluid analogizing is a fundamental cognitive process, then the question arises: Which brain processes support fluid analogizing in cognition? Several lines of evidence converge to suggest that fluid analogizing is supported by (at least) frontal processing. There have been a number of neuroimaging studies of analogizing that have implicated frontal functioning. The analogy stimuli in these earlier studies were either simple analogies (e.g., Black is to white as high is to ...?; Luo et al., 2003), or the Ravens Progressive Matrices (RPM), a visuospatial intelligence test presented as 2D multivariate spatial analogies (Christoff et al., 2001; Kroger et al., 2002; Prabhakaran, Smith, Desmond, Glover, & Gabrieli, 1997; Wharton et al., 2000). The RPM has also been used for investigations of the neural correlates of deductive reasoning (Prabhakaran et al., 1997) and reasoning underpinning relational complexity (Christoff et al., 2001; Kroger et al., 2002), each of which report a network of frontal activations. The rationale for the focus on the RPM in these studies was that it provided valid and reliable measures of the ability to solve novel problems without reference to long-term knowledge, in contrast to verbal analogies, which require semantic and content knowledge, A drawback to the RPM, however, is that responses can only be regarded as either correct or incorrect. Fluid analogizing, in contrast, elicits a range of responses, all of which could be regarded as correct, albeit with differing degrees of plausibility.

Consequently, we investigated the neural correlates of fluid analogizing by adapting the Hofstadter/Mitchell Copycat letter strings to an event-related functional magnetic resonance imaging (fMRI) experiment (Geake & Hansen, 2005). The novelty of this study lay in our attempt to reflect the inexactness of real-world reasoning (Dunbar, 2001) by soliciting preferred-answer responses, as opposed to correct answers. The main general hypothesis was that fluid analogizing tasks would activate regions of frontal cortex, including areas of significant activation reported in previous neuroimaging studies of inferential and analogical reasoning. A second hypothesis proposed a positive relationship between ADR and measures of intelligence. Twelve right-handed adults (intelligence range above-average to high) chose "best" completions (from a four-way plausible choice) of fluid letter string analogies, with a parameterized (ADR) range of difficulties. Compared with the simplest items, significant neural activations for difficult fluid analogies were found in the left superior frontal gyrus, bilaterally in the inferior and middle frontal gyri and in the anterior cingulate/paracingulate cortex (Figure 1).

[FIGURE 1 OMITTED]

These frontal areas have been previously associated with reasoning tasks involving inductive syllogisms, syntactic hierarchies, and linguistic creativity. Since the pattern of activations associated with these fluid analogizing tasks was similar to those of previous inferential reasoning tasks, especially the prefrontal cortex (PFC) activation patterns associated with the RPM, it could be argued that if success at inductive reasoning tasks requires selection and application of relevant generalized properties, then inductive reasoning requires the making of fluid analogies. Within the left inferior frontal gyrus, activated regions included Brodmann's area (BA) 44/45 (famously known as Broca's area), posterior BA 46/9, and anterior BA 9. A region-of-interest (ROI) analysis of the anterior BA 9 area showed a difference in the blood oxygen level-dependent (BOLD) (1) signal strength depending on ADR, evidence in support of our main hypothesis. Analysis of the BA 46/9 area further showed that individual subjects' BOLD activation strengths were strongly correlated ($r = 0.89$) with measures of verbal IQ as determined by the National Adult Reading Test (NART) correlation with general IQ = 0.81 (Nelson, 1991), evidence in support of our second hypothesis (Figure 2). This is a provocative result given that verbal IQ is a measure of crystallized as opposed to fluid intelligence yet correlated strongly with the neural physiological response of undertaking fluid analogy tasks. These findings provided an account of individual differences in cognitive abilities associated with fluid analogizing in terms of neural response.

That said, an obvious limitation to this study was that it employed only letter string fluid analogies. Consequently, we investigated the generalizability of fluid analogical reasoning across stimulus types with a second fMRI study involving numeric and geometric fluid analogies and other measures of intelligence (Geake & Hansen, 2006). Sixteen adult participants of IQ range normal to high responded to the plausibility of 40 fluid analogies composed of letter, number, and polygon strings with (implicit) transformation, e.g., 123 -> 124, 567 -> 568, parameterized for depth and pseudo-randomly interleaved for presentation. A symbol-counting task employing the same stimuli was used as a traditional analogical control. A battery of psychometric measures recorded individual cognitive abilities. Again, the patterns of neural activations included bilateral frontal-parietal areas, with considerable overlap in activations associated with the letter, number, and polygon analogy strings, as well as the counting task (Figure 3).

A covariate analysis of the cognitive measures with the analogy response activations revealed right PFC areas in which BOLD increases were correlated with spatial IQ scores as determined by the Ravens Advanced Progressive Matrices (RAPM). This result, where the BOLD response while fluid analogizing correlated with a spatial intelligence measure in the right prefrontal cortex, when taken together with the correlations in the previous study between the BOLD response while fluid analogizing and a language-based measure of intelligence in the left prefrontal cortex, is given the traditional lateralization bias for language (left) and spatial (right) reasoning tasks, strong evidence for our main conjecture that fluid analogizing is an underpinning process for all acts of cognition. Moreover, the strength of the correlations ($r = 0.89$) between the neurophysiological response to fluid analogizing and conventional paper-and-pencil measures of intelligence, even more remarkable given the limited range of the IQ measurements (118-132) of the participants (the NART has a ceiling of 132), suggests that high abilities at fluid analogizing might be directly indicative of intellectual giftedness, perhaps even more so than many conventional IQ subtests (Kalbfleisch, 2004). It is planned to test this provocative conjecture in future studies involving gifted and age-matched adolescent subjects.

[FIGURE 2 OMITTED]

[FIGURE 3 OMITTED]

HIGH INTELLIGENCE, FRONTAL FUNCTIONING, AND WORKING MEMORY

Notable in our results was the degree of similarity between the regions of activation associated with undertaking fluid letter string analogies and activations associated with attempting high-g-correlated items from the WAIS (Duncan et al., 2000), viz. lateral prefrontal and parietal regions. The role of the frontal cortical neurophysiology involved in high intelligence was further informed by a subsequent meta-analysis of 20 neuroimaging studies of cognition: inductive reasoning, deductive reasoning, arithmetic reasoning, linguistic reasoning (Duncan and Owen, 2000), where the centers of activation of all fell within the same regions of bilateral inferior prefrontal cortex. To explain this result, Duncan (2001) suggested that:

> [T]hroughout much of the prefrontal cortex ... the response properties of single neurons are highly adaptable.... Any given cell has the potential to be driven by many different kinds of input--perhaps through the dense interconnections that exist within the prefrontal cortex. In a particular task context, many cells become tuned to code information that is specifically relevant to this task. In this sense, the prefrontal cortex acts as a global workspace or working memory.
> (p. 824)

The salience of an adaptive account of frontal processing to fluid analogy making can be gleaned from the implications for selectional attention of relational properties over surface features--one of the hallmarks of fluid analogy making. Thus, our results inform these accounts of how frontal areas might solve higher-level problems and contribute to executive functioning--a central construct of working memory as the basic process of intelligence (Gray, Chabris, & Braver, 2003; Gray & Thompson, 2004; Rypma, Prabhakaran, Desmond, et al., 1999). Other proposed facets of working memory include a lexical buffer and a visual sketchpad (Baddely & Sala, 1998), which could account for our correlations between fluid analogizing and both verbal and spatial cognitive abilities. Duncan (2001) pointed out that selective adaptability of frontal neurons enables focused attention or emphasis on relevant inputs while filtering out irrelevant inputs. Moreover, such focused frontal information processing supports information processing in other relevant areas of the brain by maintaining persistent activation of relevant inputs from other brain areas. The combined effect of this is to create a temporary dominant active state of concern toward that particular problem. This regional involvement increasingly recruits overlapping regions of the frontal cortex as problem engagement continues.

In this way, sustained and focused thinking requires high working memory demand.

As executive cognitive control in the form of attentional focus and selective inhibition (albeit mostly unconscious) is a central function of the lateral areas of the frontal lobes (Baddeley & Sala, 1998), a main benefit of relatively enhanced frontal activity for gifted children is:

> [A] finely tuned capacity for activating (or inhibiting) the very brain regions known to play (not play) specialized roles in the performance of a given task.... That is, precocious individuals are especially facile at knowing what steps to take in solving a given intellectual problem. (O'Boyle, Benbow, & Alexander, 1995, p. 438)

Efficacious frontal functioning, then, is a neural feature of intellectual giftedness, enabling, it is argued, a propitious employment of fluid analogizing as the cognitive process that enables the various facets of working memory associated with frontal activation. A detailed neuroimaging investigation of this conjecture is also planned for the near future.

There are a number of other neuroimaging studies that provide supporting evidence for the pivotal role of frontal functioning in higher order thinking. In particular, there is evidence that the left superior frontal gyrus is used to retrieve rule-based knowledge (Goel & Dolan, 2001; Goel, Gold, Kapur, & Houle, 1997; Parsons & Osherson, 2001), that the middle frontal gyrus is involved in changes of executive functioning required to learn new rules (Strange, Henson, Friston, & Dolan, 2001), and whereas the anterior PFC is involved with resolving subgoals (Koechlin, Basso, Pietrini, Panzer, & Grafman, 1999), the left ventral inferior prefrontal cortex is specifically involved in relational integration of task complexity (Christoff et al., 2001), particularly when the task requires selection from competing alternatives (Kroger et al., 2002), and the right superior frontal gyrus, and adjacent middle frontal areas, process distant associations that may be useful in creative thought and problem-solving (Jung-Beeman, Bowden, Haberman, et al. 2004; Seger, Desmond, Glover, & Gabrieli, 2000). In allocating attentional resources to higher order decision making, the role of anterior cingulate/paracingulate cortex has been well established (Kroger et al., 2002; Parsons & Osherson, 2001), although whether this is done by initiation or inhibition remains equivocal (Knauff, Mulack, Kassubek, Salih, & Greenlee, 2002).

In addition, several neuroimaging studies report neuroanatomical correlates with IQ, with quantitative and qualitative differences between high-IQ subjects and subjects with average IQ in the focal density of both white and grey matter. In a voxel-based morphometry (VBM) study to measure brain cell density that correlated with IQ, about 6% of the grey matter volumes were distributed in the brain, with most in the frontal lobes (Haier, Jung, Yeo, Head, & Alkire, 2004). In a longitudinal MRI study of intellectual ability and cortical development in 300 children and adolescents (Shaw, Greenstein, Lerch, et al., 2006), data sampled over 6 years indicated that the trajectory of change in the thickness of the cerebral cortex, rather than cortical thickness itself, was most closely related to levels of intelligence. Notably, the thickness of the cortex was thinner in the high-IQ group when these children were young but rapidly grew, so that by the time the gifted children had reached their teens, their cerebral cortices were significantly thicker than average, especially in the prefrontal cortex.

FLUID ANALOGIZING AND CREATIVE INTELLIGENCE

For the present it could be speculated that, as a neural mechanism, fluid analogizing is a cognitive-level description of neural signal match-mismatch articulations between the brain's myriad functional modules. Such speculation is not too far removed from the concept of a global or dynamic workspace proposed by Dehaene et al. (1998). The dynamic workspace provides a "communication protocol" that allows the flow of information between the brain's many specialist functional modules, many of which do not directly interconnect. Importantly, afferent information flow is ascending hierarchical, and efferent information flow descendent hierarchical, as originally proposed by Luria (1973). Dehaene et al. suggested that such intense mobilization of neural resources gives rise to the subjective phenomenon of conscious effort. Working memory can be regarded as a cognitive-level conception of the dynamic workspace.

Fluid analogizing as a basic process of creative thinking within this dynamic workspace model can be conceptualized as describing how a distributed neural system of specialized processors with long-distance connectivity can "potentially interconnect multiple specialised brain areas in a co-ordinated, though variable manner" (Dehaene et al., 1998, p. 14529). Such neural synchronization allows possible interrelationships between problem and context to be explored by fluid analogizing with the resultant variance iteratively creating temporary solutions in working memory (Fuster, 2003). There is evidence for a relatively greater neural synchronisation in gifted subjects. In an ERP study of the visual information processing that compared gifted and average schoolchildren, Zhang, Shi, Luo, Zhao, and Yang (2006) found that gifted children have a neural network which is more spatially and temporally coordinated. A better coordinated neural network would presumably enable creatively intelligent individuals to consider more analogical combinations; that is, to keep competing ideas and concepts active in working memory. In support of such a conjecture, Carson, Peterson, and Higgins (2003) found a significant relationship between the various indicators of creativity and reduced latent inhibition, holding on-line, rather than rejecting a priori, a greater number of creative insights or solution trajectories.

Such a whole-brain conceptualization underscores an important point: that high intelligence is supported by frontal functioning within a fronto-parietal network (Gray et al., 2003). An fMRI study by Lee et al. (2006) compared adolescents from the Korean National Academy for the Gifted (RAPM > 99%) with age-matched controls. Whereas high g-loaded tasks increased activity in bilateral prefrontal regions as expected, for the gifted subjects the activations were seen in the anterior cingulate, a region involved in emotionally weighted decision making (Rolls, 1999), and the posterior parietal cortices, regions involved in forming conceptual interrelationships, especially of a quasi-spatial representation (Fuster, 2003; Luria, 1973), where the BOLD response correlated positively with RAPM measures of g. Lee et al. concluded that:

> These results suggest that superior-g may not be due to the recruitment of additional brain regions but to the functional facilitation of the fronto-parietal network particularly driven by the posterior parietal activation. (p. 578)

This could be regarded as a particular instance of Duncan's (2001) model wherein adaptive frontal functioning maintains task commitment through persistent activation of relevant inputs from other brain areas. The extent to which such neural support is more extensive and focused for gifted individuals is a manifestation of greater working memory efficacy or, in other words, a more efficient dynamic workspace (Geake & Dodson, 2005).

Further evidence for a frontal-parietal network as a feature of the gifted brain comes from an fMRI study by O'Boyle et al. (2005) of mathematically gifted male adolescents engaged in mental rotation. Whereas previous studies had shown mental rotation to be more of a right parietal activity, O'Boyle et al.'s gifted subjects demonstrated bilateral activation of the parietal lobes and frontal cortex, along with heightened activation of the anterior cingulate, during mental rotation. It was conjectured that:

> [I]t may be that enhanced (and bilateral) activation of the parietal lobes, frontal cortex, and the anterior cingulate are critical parts of an all-purpose information processing network, one that is relied upon by individuals who are intellectually gifted, irrespective of the nature of their exceptional abilities. (p. 586)

It could be noted that such a conjecture might be accounted for by our speculation that fluid analogizing represents a neural process of intermodular information filtering, or impedance matching, enabling contributions from cortical, subcortical, and cerebellar structures to measures of intelligence (Kalbfleisch, 2004).

The importance of integrated information processing together with adaptive attention lies in its manifestation as creative intelligence. A greater efficiency and extent of the intermodular network in the brains of gifted people supports their superior capacity for information processing and creative thinking. Specifically, this neural instantiation of giftedness supports a relatively enhanced executive capability. Building on a neural Darwinian account of giftedness (Geake, 1997), Geake and Dodson (2005) have constructed a neuropsychological model of high creative intelligence that incorporates these neural characteristics of giftedness. The model features the core cognitive process of fluid analogizing within a dynamic workspace to produce, in the gifted, a more efficacious working memory with relatively enhanced executive functioning (Geake, 1999), focused attention (Geake, 1996), delayed closure (Carson et al., 2003), and evaluative selection (Geake, 1997).

Creative thinking, then, involves novel conjoining, making critical comparisons, refreshing short-term memory, actively inhibiting irrelevant information while holding online interesting outliers, and evaluating and judging by utilizing wider criteria. In other words, giftedness can be conceptualized as a more efficacious neural Darwinism, where gifted people are superior on the generation of variance, selection of the most apt mental output, and efficient transmission to next iteration (Geake, 1997). Fluid analogizing underpins this creative process by privileging relationships. Whereas most people are attracted to the surface features of analogies, and hence the difficulty with transference between school subjects, the gifted are attracted to deep structures and relationships, and hence their better performance at analogizing tasks in intelligence tests. But the more important benefit is enjoyed in real-word problem-solving where it is a judicious combination of expertise (appropriate long-term memory retrieval), ability to transfer (fluid analogizing in application), and innovation (fluid analogizing in imagination) that enables giftedness as creative intelligence to flourish.

MUSICAL PRODIGIES EMPLOY FLUID ANALOGIES TO PROCESS MUSICAL INFORMATION

As a group of gifted and talented children worthy of study, musical prodigies, by typically performing at adult levels of competence while still being very young, demonstrate above-age talent development in extremis. In a study comparing estimations of musical self-coherence (operationalized as the autocorrelation function of the pitch stream) by modern-day Mozarts (typically a 12-year-old performing concerti with orchestras) vs. age-matched peers also undertaking music lessons, Geake (1996) found that executive attention accounted for over 23% of the total variance in the Mozarts' information processing measures, double that attributable to sequential processing as might be naively expected when processing a succession of notes or chords.

However, making sense of music as it is heard involves more than processing one note after another: what is being heard in the present instant must be compared with what was heard just prior, and what was heard before that, and so on over longer time periods (lags) back to the beginning of the piece. That is, making sense of music requires making a time series of musical analogies of varying lengths throughout the piece. But, in classical and jazz music at least, these various heard segments are not identical. Hence, the analogizing required for high-level musical information processing involves fluid analogizing. Such a claim is not restricted to pitch processing. Nonlinear modeling of the neurophysiological dynamics of the internal generation of rhythm also demonstrated the necessity of nonlinear or fluid analogizing to maintain a regular metric during performance (Geake & Gregson, 1999). Furthermore, it was suggested that such analogizing is facilitated by hierarchical temporal organization of the music. That is, compositional structure aids musical information processing but not to the exclusion of individual differences.

In a follow-up study of the audiational and information processing abilities of musically gifted children, using the age-normed Gordon's Musical Aptitude Profile (MAP), the superior performance on the MAP subtests by the young Mozarts correlated with higher measures on both successive and executive information processing (Geake, 1999). The MAP is a suite of probe-distractor memory tests where the answer is a nonexact analogy of the probe. That is, Gordon's MAP subtests for pitch, rhythm, and form involve making a fluid analogy between prompt and probe. Interestingly, there were no differences between gifted musicians and non-gifted age-matched peers on the MAP subtest for aesthetic preference, the one MAP subtest that does not require fluid analogizing (Geake, 1999).

Together, these results explain the extraordinarily steep learning curve that the music prodigies of the first study demonstrated, typically learning a full sonata in a week of practice. An obvious characteristic of this cohort was, in contrast to most 12-year-old music students, how much they enjoyed their practice. Clearly, such high motivation was part of a positive feedback cycle where success built on success. Here the success of these modern-day Mozarts seemed to be the result of superefficient practice, where errors and slips were overlooked, or at least not repeated (again, unlike typical music students). Expertise was developed through practice in which errors were minimized and certainly not unwittingly reinforced. This involved making sense of the music in terms of its temporal coherence, as described above, which in turn requires recourse to fluid analogies. It was the analogizing between current or planned performance and the previous, over varying time lags, that provided the feedback necessary to eliminate error, improve interpretation, and improve the quality of the performance. An earlier demonstration of fluid analogizing within musical improvized performance was observed in a differentiated junior secondary school music program for musically gifted and talented students (Andreasen & Geake, 1998). Through a planned process of musical analyses, compositional variation, delayed inhibition before selection, and performance critique, the various stages of Geake and Dodson's (2005) model of creative intelligence were explicitly employed toward high-level musical performance outcomes.

CONCLUSION

This review has attempted to contribute to the broad question of which individual neural differences uniquely characterize giftedness by proposing fluid analogizing as a fundamental cognitive process in which abilities vary across individuals. In sum, the gifted are better at fluid analogizing. A neuroimaging program of fMRI studies into the neural bases of fluid analogizing shows it to be associated with frontal cortical processes within a fronto-parietal network, often articulating with subcortical and cerebellar structures (Kalbfleisch, 2004) necessary for higher order thinking.

The neural activations observed with fluid analogizing are similar to those associated with undertaking items from conventional IQ tests because of a common dependence on working memory, the gifted having a greater working memory capacity and capability. This in turn is due to a relatively greater ability at fluid analogizing; the neural resources dedicated to fluid analogizing in our fMRI studies correlate positively with conventional measures of intelligence. As a cognitive construct, fluid analogizing informs accounts of creative intelligence, not least in prodigious musical performance as an exemplar of giftedness actualized as expertise through the (unconscious) application of fluid analogizing.

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(1) The BOLD signal is a measure of change (decrease) in the concentration of deoxygenated blood in local neural vascolature, caused by a dilation in the local capillaries, which in turn is presumed to be caused by an increase in local neuronal activity in response to the experimental stimuli. The BOLD signal is the most common dependent variable in fMRI studies to date.

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