

The Neurobiology of Giftedness

John G. Geake

Westminster Institute of Education

Oxford Brookes University

United Kingdom

ABSTRACT

Gifted children learn more rapidly and efficiently than others, presumably due to neurophysiological differences that affect neuronal efficiency. Data from many neuroimaging studies support this conjecture. Gifted subjects have greater interconnectivity between different areas of their brains, the coordination and integration of which is supported by precociously developed frontal cortical areas. This supports a suite of high-level neuro-cognitive abilities including a relatively enhanced executive capability, with a more efficacious working memory. These precociously developed neurobiological functions combine to enable high-level creative intelligence as a central characteristic of general giftedness, along with rapid information processing, heightened cognitive control, and a desire for top-down perspectives. Implications for pedagogy and curriculum include:

- Set tasks with high working memory demands, e.g. tasks with multiple components;
- Reduce quantity of small tasks, e.g. repetitive maths examples;
- Use challenge tests to evaluate prior knowledge;
- Design assessment with higher-order Bloom's taxonomies – analysis, synthesis; Use above-age learning materials;
- Group gifted kids with other gifted kids, regardless of age;

- Employ subject specialist mentors, e.g. retired professionals;
- Offer lessons on topics beyond the regular curriculum.

INTRODUCTION

In the early 21st Century, nearly a decade after ‘The Decade of the Brain’, when brain-based explanations of human cognitive characteristics are expected, (if not always available to a completely satisfactory degree), how can we explain giftedness?

Within a diverse literature, there are plenty of cognitive behaviours which characterise giftedness for which we can seek neural level descriptions. Among such characteristics, the following (at least) enjoy general acceptance (Geake, 2007a).

- Gifted children are precocious in their intellectual development, evidenced by IQ measures several standard deviations above the normed chronological average (Gross, 2004). Of course in many circumstances, such as selection for differentiated school programmes, this is definitional. For most laboratory studies, including those reviewed below, that giftedness incorporates high IQ is tautological.
- Gifted children exhibit superior cognitive control characteristics, including focussed attention (Geake, 1996), evaluative selection (Geake, 1997), and delayed closure (Vigneau, Caissie & Bors, 2006).
- Gifted children demonstrate rapid information processing (O’Boyle, Benbow & Alexander, 1995; O’Boyle, 2000; Singh & O’Boyle, 2004), typically requiring much less repetition for learning, although sometimes,

paradoxically, being slower at lower-level classroom answers, presumably due to interpreting the question at a higher level than was intended, and thus processing too much information (Gross, 2004).

- Gifted children seek top-down understanding (Clark, 1997). Slaking their seemingly endless thirst for knowledge could become overwhelming were it not for a concomitant drive to conceptualise with big-picture perspectives, with abstract higher-order categorisations (Geake, Cameron, Clements & Phillipson, 1996). Such cognitive mapping is supported by comparatively larger working memory capacities (Geake, 1999; 2006b).
- Gifted children are highly creative, making original inter-subject connections with relative ease (Kanevsky & Geake, 2005; Geake & Dodson, 2005), aided by predilections for abstract symbolic manipulation (Geake, 2006a), and for readily comprehending sub-text (Bacon, Geake, Lea-Wood, McAllister & Watt, 1991).

To account for such a suite of behaviours that characterise giftedness, presumably:

[s]uch individual differences can be attributed to neurophysiological differences that affect neuronal efficiency. (Geake, 1997, p. 28)

But what differences in neural function result in giftedness as opposed to pathology?

As interesting as the question might be, it is not the purpose of this review to consider conjectured ‘fine lines’ between genius and madness, or to contrast the neuro-cognitive characteristics of savants with those of the ‘normally’ gifted (Geake, in

progress). Rather, this review will note some neuroscientific evidence for the neural bases of the five typically gifted cognitive behaviours listed above. For a more detailed review of particular pieces of this research see Geake (2007a).

GIFTED CHILDREN ARE PRECOCIOUS IN THEIR INTELLECTUAL DEVELOPMENT

Above-age testing has been one successful approach to more accurately assess the academic and intellectual abilities of gifted children whose scores on age-normed standardised tests are at or near ceiling (Gross, 2004). The assumption behind above-age testing is that gifted children are more similar (at least cognitively), to older children than to their same-age peers. This assumption is not unfounded. In an electroencephalographic (EEG) study comparing the (resting alpha power) EEG of 30 gifted adolescents from the Iowa Study of Mathematically Precocious Youth (CY-TAG) with 30 age-matched peers and 30 college students, Alexander, O'Boyle and Benbow (1996) found that, while there were differences in alpha band power over the temporal and parietal lobes:

there were no differences in alpha power at the frontal and occipital lobe locations between gifted adolescents and college age subjects suggesting that the two groups have a similar level of brain maturation for these regions. (p. 30)

In other words, the frontal lobes of the young gifted subjects seemed to be operating with the equivalent maturity of students some five years older already in university. This interpretation raises a question: To what extent is such cognitive precocity the

outcome of precocious neural development, i.e., are the brains of gifted children structurally more like the brains of older children than those of same-age peers? Evidence to address this question was provided by a six-year longitudinal magnetic resonance imaging (MRI) study of intellectual ability and cortical development in 300 children and adolescents (Shaw et al, 2006). (MRI data consists of structural images of brain tissue – white and grey matter). Here, these data showed that the trajectory of change in the thickness of the cerebral cortex (the outer layer of grey matter most implicated in intellectual functioning), rather than cortical thickness per se, was most closely related to the children's levels of intelligence. In particular, the cortices of the high-IQ group were thinner when these children were young, but grew so rapidly that by the time the gifted children were adolescents, their cerebral cortices were significantly thicker than average, especially the prefrontal cortex. In sum, the neuroanatomical development of intelligence is dynamic.

Shaw et al.'s conclusion in turn raises questions of causative contributions (beyond the remit of their study), such as genetic endowment on the one hand, and socio-economic and educational environments on the other. To this end, over a decade earlier, O'Boyle and Benbow (1990) speculated that one source of such precocious neural development was differential prenatal exposure to testosterone, one of several neurotoxic hormones which mediate epigenetic brain organisation.

GIFTED CHILDREN EXHIBIT SUPERIOR COGNITIVE CONTROL CHARACTERISTICS

Whereas executive functioning (cognitive control) involves a suite of interacting aspects of working memory, including top-down attention, delayed closure, task

evaluation and updating (Baddeley & Sala, 1998), data from a range of neuroimaging studies of the neural correlates of various aspects of executive functioning have consistently converged on bilateral activations of the prefrontal cortex (PFC) (e.g., Koechlin et al., 1999;; Christoff et al., 2001; Parsons & Osherson, 2001; Strange et al., 2001; Kroger et al., 2002). Two neurobiological questions follow: 1. Do differences in measures of intelligence correlate with differences in PFC activation? 2. Do differences in measures of intelligence correlate with differences in structural features of the PFC?

Evidence to address the first question comes from a Positron Emission Tomography (PET) study (measuring neural glucose metabolism) by Duncan and colleagues in which neural activations in response to high g-loaded (i.e., difficult) IQ test items were contrasted with activations in response to low g-loaded (i.e., easier) IQ test items (Duncan et al., 2001). Thinking about difficult IQ test items, whether spatial or verbal, involved the bilateral PFC. Consistent results were found by Lee et al. (2006) in a functional magnetic resonance (fMRI) study (measures experimentally induced changes in neural vasculature, the BOLD (blood oxygen level dependent) response) which compared gifted and age-matched adolescents on high-g and low-g loaded IQ test items; in the gifted group, high g-loaded tasks increased activity in bilateral PFC regions. And in a series of fMRI studies of fluid analogising (described more fully below), Geake and Hansen found positive linear correlations between BOLD changes while engaged in analogising with measures of high verbal IQ (National Adult Reading Test, NART) in the left lateral PFC (Geake & Hansen, 2005), and with measures of high spatial IQ (Raven's Advanced Progressive Matrices, RAPM) in right lateral PFC (Geake & Hansen, 2006).

Evidence with which to address the second question about IQ correlates with differences in neural structure comes from a voxel-based morphometry (VBM) study (uses MRI data to measure quantitative individual differences in grey and white matter) of brain cell density in which most of the 6% of grey matter volumes distributed throughout the brain which correlated with IQ were found in the PFC (Haier et al., 2004).

In sum, gifted individuals have relatively enhanced structural, and hence functional, neurobiology in the PFC regions responsible for cognitive control, and working memory.

GIFTED CHILDREN DEMONSTRATE RAPID INFORMATION PROCESSING

The foregoing focus on the PFC, however, does not imply that the frontal cortex is the exclusive brain region involved in supporting giftedness. Rather, high intelligence is supported by a fronto-parietal network (Gray, Chabris & Braver, 2003; Gray & Thompson, 2004). The reason is that the cognitive control afforded by frontal functioning requires persistent activation of relevant inputs from other brain areas to maintain task commitment (Duncan, 2001).

The extent to which such neural support is more extensive and focussed for gifted individuals is presumably a manifestation of greater working memory efficacy (Rypma et al., 1999). Evidence for the effective deployment of a fronto-parietal network by gifted individuals model is provided by two studies. Zhang et al. (2006),

in an ERP study of the information processing involved during a visual search task with gifted and average school children in China, explained their results by suggesting that the gifted children had better spatially and temporally coordinated neural networks. And Lee et al. (2006) in an fMRI study in Korea found that gifted primary and secondary school children displayed stronger activations in their posterior parietal cortices, regions involved in forming conceptual inter-relationships, especially of a quasi-spatial representation (Luria, 1973). 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)

Consistently, an fMRI study by O'Boyle et al. (2005) of mathematically gifted male adolescents engaged in mental rotation also showed bilateral activation of the parietal lobes and frontal cortex. O'Boyle et al. suggested that:

the parietal lobes,[and] frontal cortex ... 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)

Importantly, enhanced bilaterality seems to be a characteristic neurobiological feature of information processing by gifted individuals (Singh & O'Boyle, 2004), as a suite of psychophysical experiments has shown (O'Boyle, Benbow & Alexander, 1995).

Moreover, it has been more recently suggested that the cerebellum plays an important

rehearsal role in information processing; consequently, heightened cerebellar functioning is another neurobiological characteristics of giftedness (Vandervert & Liu, 2007).

The combined effect of these neurobiological features for processing information is to create a temporary dominant active state of concern towards a particular problem, increasingly recruiting overlapping regions of the frontal cortex as problem engagement continues (Duncan, 2001). By this account it is clear why enhanced working memory capacity, as supported by efficacious frontal functioning and structure, is a hallmark of intellectual giftedness, enabling gifted people to achieve superior measures in IQ tests, as well as high levels of creative intelligence through task adaptation and selectivity (described more fully below) (Geake & Dobson, 2005).

GIFTED CHILDREN SEEK TOP-DOWN UNDERSTANDING

In describing giftedness at a neurobiological level, it is also important to consider differences in how information is perceived and utilised by gifted individuals. To this end, musical prodigies provide an informative group of gifted and talented children to study. In an information processing study of musical coherence in young Mozarts, Geake (1996) found that cognitive control processing was most important for outstanding musical ability. He conjectured that:

For gifted young musicians, it is their superior use of executive or metacognitive strategies [mediated by the frontal cortex], such as inward-directed attention, that contributes most towards their remarkable abilities. (p.

41)

The point of measuring musical coherence as a critical aspect of musical information processing was that making sense of music requires a top-down perspective: 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 back to the beginning of the piece. But whereas compositional structure, such as hierarchical temporal organisation of the music, can assist musical information processing (Geake & Gregson, 1999), it was individual differences in their predilection for making top-down musical sense through processing musical coherence, aided by their enhanced working memory capacities for processing such musical information (Geake, 1999), that enabled these modern-day Mozarts to achieve mature levels of performance of the standard repertoire, and engage in hours of highly motivated and efficient practice (Geake, 1996).

The quest for top down understanding is also evident among young mathematically gifted children. In an information processing study which operationalised Vygotsky's Zone of Proximal Development (ZPD) in elementary school children undertaking mathematical pattern problems, Kanevsky and Geake (2005) found that the gifted children sought top-down, meta-level hints and suggestions from their teacher rather than item-specific suggestions which were preferred by their peers. And similarly to Geake's musical prodigies, the mathematically gifted children here also had higher measures of cognitive control, as described by Vygotsky's colleague Luria (1973).

GIFTED CHILDREN ARE HIGHLY CREATIVE

The neurobiological characteristics of giftedness which support high levels of executive functioning and working memory, viz., efficacious PFC functioning, and enhanced bilaterality of an extended cortical network, afford benefits to gifted individuals through:

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 [sic] what steps to take in solving a given intellectual problem. (Baddeley & Sala, 1998, p. 438)

In other words, efficacious executive cognitive control involves attentional focus and selective inhibition (albeit mostly unconscious). These neurobiological and related cognitive characteristics have been combined in a neuropsychological model of high creative intelligence (Geake & Dobson, 2005). This model of creative intelligence features fluid analogising, analogies with several plausible but no necessary correct solutions (Hofstadter, 1995; 2001), as the vehicle by which dynamic information processing occurs in the brain. Fluid analogising enables the generation of candidate relationships between new information and selected items from long-term memory store. Consequently, it has been argued (in much greater detail than is possible here) that a keen facility for fluid analogising is a cognitive hallmark of giftedness (Geake, 2007b). Geake and Dobson's model also indicates how creative solutions or ideas are selected from candidate variance with recourse to both internal and external (social) criteria, which in turn inform further creative thinking. The model draws on an earlier neural Darwinian description of giftedness (Geake, 1997) in which gifted individuals

in search of a creative solution to a problem generate greater variance, employ more innovative selection criteria, and store the outcomes more efficiently in long-term memory for later use. Moreover, Geake and Dobson (2005) suggest, gifted individuals delay closure on creative thinking tasks to accommodate the more extensive information processing that they typically employ, and not to discard outlier thoughts too early. There is both behavioural (Carson, Peterson & Higgins, 2003) and psychophysical (Vigneau, Caissie & Bors, 2006) evidence for this suggestion.

There is also neuroimaging evidence for the primary role of fluid analogising in creative cognition. Geake and Hansen (2005; 2006; in progress) used fMRI to study the neural activity of above-average IQ subjects to assessing the plausibility of fluid analogy symbol strings (Hofstadter, 1995). Consistently with previous neuroimaging studies of the neural correlates of higher-level reasoning (Prabhakaran et al., 1997; Wharton et al., 2000; Luo et al., 2003), activations were found in a bilateral fronto-parietal network. As noted above, Geake and Hansen (2005) also found two areas of left PFC where neural activity during fluid analogising correlated with verbal IQ as determined by knowledge of irregular words (NART). In other words, IQ as determined by a measure of crystallised intelligence predicted neural activation in regions for working memory engaged in a fluid or creative analogy task. A wider knowledge base, it seems, can support a greater facility for fluid thinking, at least in high-IQ subjects. More recently, Geake and Hansen (2006) demonstrated that fluid analogical thinking across different fluid analogy types recruits the same fronto-parietal network; further evidence for the claim of fluid analogising as a core cognitive process. Additionally, as noted above, Geake and Hansen (in progress) found an area of the right frontal cortex where neural activity during fluid analogising

across types positively correlated with IQ as determined by high-level spatial reasoning (RAPM). This pair of correlates, between verbal/spatial measures of IQ and lateralised PFC, suggests that a gifted person's success at specific intellectually demanding tasks is significantly determined by how well their brain enables fluid analogising as a fundamental cognitive process.

Certainly, a proficiency at fluid analogical reasoning and its application to creative thinking, analysing sub-text, decoding symbolic relationships, and so on, could explain giftedness in a number of academic areas, including philosophy (Bacon et al., 1991), mathematics (Geake, 2006a), science (Geake et al., 1996), and music (Andreasen & Geake, 1998; Geake, 2007b). For example, the cognitive processes required of musically gifted children involved in highly creative and effective compositional improvisation, viz., planned musical analyses, compositional variation, delayed inhibition before selection, and performance critique (Andreasen & Geake, 1998), are similar to those required of mathematically gifted students in arriving at optimally parsimonious or aesthetically elegant solutions (Geake, 2006a). In both cases, proficiency at fluid analogising can explain how these processes are seamlessly and unconsciously enabled in the brain.

CONCLUSION

Although neuroimaging studies of brain structure and function have been conducted for well over a decade, the complexity of the human brain suggests that cognitive neuroscience as a research discipline is still in its infancy. And within this nascent field, studies of group differences necessarily await further publication of robust and replicated data about the brain functioning of the general population. Nevertheless,

findings from those few studies which have compared gifted with non-gifted subjects, together with correlational studies involving conventional measures of intelligence, are consistent. The neurobiology of giftedness is characterised by high-level prefrontal cortical functioning within a bilateral fronto-parietal network which, among other things, supports enhanced executive capability including a more efficacious working memory in gifted people. By conceptualising the necessary cognitive processes to enable efficacious information processing within such an extended cortical network as fluid analogising, common characteristics of giftedness across various academic and creative endeavours can be accounted for, including precocious talent, rapid information processing, heightened cognitive control, and a desire for top-down perspectives. Hopefully, as the field of cognitive neuroscience matures, neurobiological accounts of the many other cognitive and behavioural characteristics of giftedness will be forthcoming. Consequently, research into how human brains enable high intelligence seems good career advice for many of today's gifted children.

REFERENCES

- Alexander, J. E., O'Boyle, M. W. & Benbow, C. P. (1996). Developmentally advanced EEG alpha power in gifted male and female adolescents. *International Journal of Psychophysiology*, 23, 25-31.
- Andreasen, F. & Geake, J. G. (1998). A differentiated Year 7 music programme for musically gifted and talented students. *Gifted*, 103, 28-30.
- Baddeley, A. & Sala, S. D. (1998). Working memory and executive control. In A. C. Roberts, T. W. Robbins & L. Weiskrantz (Eds.). *The prefrontal cortex: Executive and cognitive functions*. Oxford University Press, Oxford, pp. 9-21.

- Bacon, M., Geake, J. G., Lea-Wood, S., McAllister, H. & Watt, N. (1991). Sum
Insight: Understanding Our World Through Logic, Mathematics and
Philosophy. In M. Goodall & B. Culhane (Eds.). *Teaching strategies for a clever
country*,. The Australian Association for the Education of the Gifted and
Talented, Melbourne, pp. 114-122.
- Carson, S. H., Peterson, J. B. & Higgins, D. M. (2003). Decreased latent inhibition is
associated with high-functioning individuals. *Journal of Personality and Social
Psychology*, 85(3), 499-506.
- Christoff, K., Prabhakaran, V., Dorfman, J., Zhao, Z., Kroger, J. K., Holyoak, K. J. &
Gabrieli, J. D. (2001). Rostrolateral prefrontal cortex involvement in relational
integration during reasoning. *NeuroImage*, 14, 1136-1149.
- Clark, B. (1997). *Growing up gifted* (5th Edn.). Upper Saddle River, NJ: Prentice Hall.
- Duncan, J. (2001). An adaptive coding model of neural function in prefrontal cortex.
Nature Reviews Neuroscience, 2, 820-829.
- Duncan, J., Seitz, R. J., Kolodny, J., Bor, D., Herzog, H., Ahmed, A., Newell, F. N. &
Emslie, H. (2000). A neural basis for general intelligence. *Science*, 289, 457-
460.
- Geake, J. G. (1996). Why Mozart? An information processing account of musical
abilities, *Research Studies in Music Education Journal*, 7, 28-45.
- Geake, J. G. (1997). Thinking as evolution in the brain: Implications for giftedness.
Australasian Journal of Gifted Education, 6(1), 27-33.
- Geake, J. G. (1999). An information processing account of audiatonal abilities.
Research Studies in Music Education, 12, 10-23.
- Geake, J. G. (2006a). Mathematical brains. *Gifted and Talented*, 10(1), 2-7.

- Geake, J. (2006b). The neurological basis of intelligence: A contrast with 'brain-based' education. *Education-Line*,
(<http://www.leeds.ac.uk/educol/documents/156074.htm>).
- Geake, J. G. (2007a). Neuropsychological characteristics of academic and creative giftedness. In L. V. Shavinina (Ed.) *International handbook of giftedness*, Springer Science (in press).
- Geake, J. G. (2007b). High abilities at fluid analogising: A cognitive neuroscience construct of giftedness. *Roeper Review* (in press).
- Geake, J. G. (2008) Neural interconnectivity and intellectual creativity: Giftedness, savants, and learning styles. In T Balchin & B. Hymer (Eds) *Companion to Gifted Education*, Routledge (in press).
- Geake, J. G., Cameron, C., Clements, D., & Phillipson, S. (1996). Science for Gifted Students: Learning from the Lorax. In M. McCann & F. Southern (Eds.). *Fusing talent: Giftedness in Australian classrooms*, The Australian Association for the Education of the Gifted and Talented, Melbourne, pp. 41-66.
- Geake, J. G. & Gregson, R. A. M. (1999). Modeling the internal generation of rhythm as an extension of nonlinear psychophysics. *Musicae Scientiae*, 3(2), 217-236.
- Geake, J. G. & Dodson, C. S. (2005). A neuro-psychological model of the creative intelligence of gifted children. *Gifted & Talented International*, 20(1), 4-16.
- Geake, J. G. & Hansen, P. (2005). Neural correlates of intelligence as revealed by fMRI of fluid analogies. *NeuroImage*, 26(2), 555-564.
- Geake, J. G. & Hansen, P. C. (2006). *Structural and functional neural correlates of high creative intelligence as determined by abilities at fluid analogising*, Society for Neuroscience Annual Meeting, Atlanta, Georgia, 17 October.

- Geake, J. G. & Hansen, P. (in progress). Neural correlates of fluid and crystallised contributions to creative intelligence as determined by abilities at fluid analogising.
- Gray, J. R., Chabris, C. F. & Braver, T. S. (2003). Neural mechanisms of general fluid intelligence. *Nature Neuroscience*, 6(3), 316-322.
- Gray, J. R. & Thompson, P. M. (2004). Neurobiology of intelligence: science and ethics. *Nature Reviews Neuroscience*, 5(June), 471-482.
- Gross, M. U. M. (2004). *Exceptionally gifted children* (2nd ed.). Routledge Falmer, London.
- Haier, R. J., Jung, R. E., Yeo, R. A., Head, K. & Alkire, M. T. (2004). Structural brain variation and general intelligence. *NeuroImage*, 23(1), 425-433.
- Hofstadter, D. R. (1995). *Fluid concepts and creative analogies*. Basic Books, New York.
- Hofstadter, D. (2001). Analogy as the core of cognition. In D. Gentner, K. J. Holyoak, & B. N. Kokinov (Eds.). *The analogical mind: Perspectives from cognitive science*, MIT Press, Cambridge, MA, pp. 499-538.
- Kanevsky, L. S. & Geake, J. G. (2005). Validating a multifactor model of learning potential with gifted students and their peers. *Journal for the Education of the Gifted*, 28(2), 192-217.
- Knauff, M., Mulack, T., Kassubek, J., Salih, H. R. & Greenlee, M. W. (2002). Spatial imagery in deductive reasoning: a functional MRI study. *Brain Research: Cognitive Brain Research*, 13, 203-212.
- Koechlin, E., Basso, G., Pietrini, P., Panzer, S. & Grafman, J. (1999). The role of the anterior prefrontal cortex in human cognition. *Nature*, 399, 148-151.

- Kroger, J. K., Sabb, F. W., Fales, C. L., Bookheimer, S. Y., Cohen, M. S. & Holyoak, K. J. (2002). Recruitment of anterior dorsolateral prefrontal cortex in human reasoning: a parametric study of relational complexity. *Cerebral Cortex*, 12, 477-485.
- Lee, K. H., Choi, Y. Y., Gray, J. R., Cho, S. H., Chae, J.-H., Lee, S., & Kim, K. (2006). Neural correlates of superior intelligence: Stronger recruitment of posterior parietal cortex. *NeuroImage* 29(2), 578-86.
- Luo, Q., Perry, C., Peng, D., Jin, Z., Xu, D., Ding, G. and Xu, S. (2003). The neural substrate of analogical reasoning: an fMRI study. *Brain Research: Cognitive Brain Research*, 17, 527-534.
- Luria, A. R. (1973). *The working brain*. Basic Books, New York.
- O'Boyle, M. W. (2000). Neuroscientific research findings and their potential application to gifted educational practice. *Australasian Journal of Gifted Education*, 9(1), 6-10.
- O'Boyle, M. W. & Benbow, C. P. (1990). Enhanced right hemisphere involvement during cognitive processing may relate to intellectual precocity. *Neuropsychologia*, 28(2), 211-6.
- O'Boyle, M. W., Benbow, C. P. & Alexander, J. E. (1995). Sex differences, hemispheric laterality, and associated brain activity in the intellectually gifted. *Developmental Neuropsychology*, 11(4), 415-443.
- O'Boyle, M. W., Cunnington, R., Silk, T., Vaughan, D., Jackson, G., Syngeniotis, A., & Egan, G. (2005). Mathematically gifted male adolescents activate a unique brain network during mental rotation. *Cognitive Brain Research*, 25, 583-587.

- Parsons, L. M. & Osherson, D. (2001). New Evidence for Distinct Right and Left Brain Systems for Deductive versus Probabilistic Reasoning. *Cerebral Cortex*, 11, 954-965.
- Prabhakaran, V., Smith, J. A., Desmond, J. E., Glover, G. H. & Gabrieli, J. D. (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.
- Rypma, B., Prabhakaran, V., Desmond, J. E., Glover, G. H. & Gabrieli, J. D. (1999). Load-dependent roles of frontal brain regions in the maintenance of working memory. *NeuroImage*, 9, 216-226.
- Singh, H. & O'Boyle, M. W. (2004). Interhemispheric interaction during global-local processing in mathematically gifted adolescents, average-ability youth, and college students. *Neuropsychology*, 18(2), 671-677.
- Strange, B. A., Henson, R. N., Friston, K. J. & Dolan, R. J. (2001). Anterior prefrontal cortex mediates rule learning in humans. *Cerebral Cortex*, 11, 1040-1046.
- Vandervert, L. R. & Liu, H. (2008) How Working Memory and the Cognitive Cerebellum Collaboratively Produce the Child Prodigy. In L Shavinina (Ed) *International handbook of giftedness*, Springer Science, (in press).
- Vigneau, F., Caissie, A. F. & Bors, D. A. (2006). Eye-movement analysis demonstrates strategic influences on intelligence. *Intelligence*, 34, 261-272.
- Wharton, C. M., Grafman, J., Flitman, S. S., Hansen, E. K., Brauner, J., Marks, A. & Honda, M. (2000). Toward neuroanatomical models of analogy: a positron emission tomography study of analogical mapping. *Cognitive Psychology*, 40, 173-197.

Zhang, Q., Shi, J., Luo, Y., Zhao, D. & Yang, J. (2006). Intelligence and information processing during a visual search task in children: an event-related potential study. *Neuroreport*, 17(7), 747-752.