MATHEMATICS AND GIFTEDNESS: INSIGHTS FROM EDUCATIONAL NEUROSCIENCE

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Exceptional performance, or giftedness, in mathematics is complicated by the variety of conceptual approaches to studies of giftedness as well as the broad and diverse nature of mathematics as taught in modern educational institutions. This paper outlines approaches to giftedness in mathematics that are based in studies of cognition within the discipline of educational neuroscience, approaches that conceptualise giftedness within a context that is sensitive to modern biology and, at the same time, inclusive of modern research in the social and behavioural sciences. Based on such approaches, exceptional performance in mathematics is discussed in relation to cognition and performance as a product of internal processing and environmental connectivity of the human organism. Such approaches have facilitated the development of an overarching framework for learning and memory that may enable a view, within the constraints of empirical science, of educational concepts related to exceptional performance. This framework may provide useful insights into the identification and education of students who may be gifted in mathematics.

Introduction

Exceptional performance, or giftedness, in mathematics appears to be a topic of great interest to researchers and teachers worldwide and there appears to be no lack of studies of the mathematically gifted. There appears to be, however, little in the way of common ground between many such studies, or studies of giftedness and cognition more generally, with the differing approaches used seemingly based in concepts and assumptions that appear to bear little relation to each other. There appears to be also no overall conceptual framework within which to compare such studies (e.g., Samuels, 2009) and, perhaps as a result, no overarching conceptualisation of giftedness as an aspect of cognition and behaviour (e.g., Kaufman & Sternberg, 2008). Studies of giftedness in mathematics appear, additionally, to lack cohesion due to the broad and diverse nature of the subject of mathematics as taught in modern educational institutions (e.g. Davis, 2003; Organization for Economic Cooperation and Development (OECD), 2003). There appears to be also a lack of cohesion apparent in disagreement about empirical, or even descriptive, comparisons of performance across cohorts in the many categories of the subject of mathematics. This complex situation is given an added dimension of arguments about whether educational institutions can function effectively in the educational development of the gifted (e.g., Diezmann & Watters, 2002; Ericsson, Nandagopal & Roring, 2009; Freeman, 2006) and by the view that studies of gifted performance in mathematics may be directed only at the aspects of mathematics that are determined as valuable in a particular society, depending on who is making such determinations and on their rationale for any such determination (Hertzog, 2009; Kaufman & Sternberg, 2008).

There have been, however, attempts to investigate overarching conceptualisations of cognition, and to investigate gifted performance within such conceptualisations. Modern educational neuroscience, for example, has attempted to incorporate an evolutionary perspective into studies of human cognition in order to place such studies in a context of human interaction with environment, a context that includes social interaction and other aspects of behaviour (e.g., Cotterill, 2001; Edelman, 1987; Margoliash & Nusbaum, 2009). Some such research has merged concepts derived from evolutionary biology and studies of cognitive function with concepts derived from education and the information sciences (e.g., Buss, 1999; Geary, 2005; Sweller, 2007, 2010) and some research has, in turn, merged such concepts with those related to connectivity of processes and pathways in organismal and non-organismal structures and systems (e.g., Barabasi, 2002; Buchanan, 2002; Sporns, Tononi & Kötter, 2005).

The results from such interdisciplinary and combination studies have been used to erect a broader, more flexible framework that describes learning and memory processes in terms of information processing systems more generally (e.g., Woolcott, 2009a, 2009b, 2010a, 2010b). Mathematics education, within this framework, can be viewed in many ways as similar to education in any subject category at any level of a broad spectrum of performance. This framework suggests further that, in treating a human individual as a information processing system, there may be differing, but sometimes overlapping, component information systems that may process information in different ways and over different time frames, but which may contribute to an assessable performance in any culturally-valued subject, not just mathematics. In considering exceptional performance in mathematics, therefore, it may be useful to consider aspects of an individual's performance that give an individual a degree of expertise, both within and across a number of culturally-valued knowledge domains.

Mathematics, performance, and educational neuroscience

In the modern age, mathematics learning is an important part of the societal accumulation of culture (knowledge and skills) and this learning is assessed, as is all learning, through observation of performances based in muscular contractions that indicate any resultant memory storage (Cotterill, 2001; Llinás, 2001). The types of performance vary from simple eye blinks to complex sequences of movement seen in sports performances, and include talking, reading and writing. Learning and memory processes and their relationship to performances in motor tasks have been the subject of considerable recent research both in the natural sciences and the social and behavioural sciences, and some of this research has been directed at examining individuals who demonstrate above-normal performances that are valued in particular societies. This includes performances that exceed the normal in pen and paper tests, such as in the Mathematics Olympiads, but also those performances that demonstrate other types of above-normal expertise, such as seen on the concert platform, in the chess arena, and on the sporting field; at various levels from local and national through to international (e.g., Ericsson, 2005; Zhu, 2007). Such assessments of expertise may be largely normreferenced with standardised intelligence tests, competitions, or other types of performance assessments conducted with this in mind (e.g., Vialle & Rogers, 2009). Some such assessments may be used to grade individuals for various reasons, for example, in order to assign monetary or other incentive awards in competitions. Although such performance assessments are not always used in any directly formative way, they may be used to indicate progress towards a goal of increased expertise or expert knowledge—for example, through guided practice (Ericsson et al., 2009). In institutional education, such assessments may serve as a guide to the quality and content of education that is provided to some students within subjects or within year groups and, recently at least, have been used to determine the allocation of resources, including an improved teacher to student ratio, to individual students or groups of students identified as gifted, and this includes those students gifted in mathematics (Moon, 2007; Vialle & Rogers, 2009).

As well as research into examining comparative performance, there has been also research into the determination of potential future performance, with support obtained for the effectiveness of some such determinations—for example, in assessments used to assess potential ability in mathematics and to assist in development of training regimes (e.g., O'Boyle, 2005). Although results from some assessments used to determine potential academic ability, such as intelligence quotient (IQ), spatial intelligence, or crystallised intelligence assessments have been correlated with academic performance in mathematics, there are limitations in applying such results to programs designed to increase expertise (e.g., Haier, 2009). Haier and associates (see, for example, Colom et al., 2009; Haier, 2009; Haier & Jung, 2008) have, however, developed a neural model, the parieto-frontal integration theory (P-FIT) that correlates the amount of grey matter (neuronal cell bodies) activated across a number of different brain regions with test scores from several such assessments, and this model may be useful in determining general intelligence, at least, based on the brain's measurable characteristics. There may be, however, many other factors that may play a role in both performance and ability (Samuels, 2009), with quick processing time—which is linked to white matter (neuronal connections)—also likely to play a key role in any assessment of potential intelligence (e.g., Haier, 2009).

Giftedness, including giftedness in mathematics, has been related to gender and age differences (e.g., Haier, Jung, Yeo, Head & Alkire, 2005; Halpern et al., 2007; Shaw et al., 2006) and exceptional performance in mathematics, specifically, has been linked with hemispheric bias and interhemispheric connectivity (O'Boyle, 2005) as well as developmental variation *in utero* (Baron-Cohen, 2003) in human males. It has been difficult, however, to relate giftedness to specific genetic attributes and Plomin and associates (e.g., Davis et al., 2007) have suggested that this is because the genes that contribute to superior learning and memory and related performances, may be generalist genes that contribute to development of many parts of the human organism. Further, modern research in learning and memory has also indicated that some types of giftedness may not be subject-specific, being related to general attributes of a human cortical advantage, such as a superior ability to generalise, superior attentional or working memory processes, or superior ability in problem solving. Some researchers, for example, have related superior working memory and attention to high scores in assessments of the general factor of intelligence (*g* factor) or fluid intelligence (Colom et al., 2007). Such superior functionality has been considered a neuropsychological characteristic of gifted people (Geake, 2009a). Although executive function, including working memory (short-term memory) and related inhibitory processes, has been implicated specifically in mathematics performances (e.g., Bull, 2008), this may be largely because such processes relate to generalised skills that are concerned with the utilisation of strategies. Such neuronal processes appear to be related also to creativity, adding support to the suggested relationships between intelligence, giftedness, and creativity (e.g., Cotterill, 2001; Geake, 2009a; Jung et al., 2009).

Some recent studies have attempted to describe fully the neuronally-based pattern analysis carried out during mathematics by comparing brain function in individuals with savant syndrome, including individuals with autism spectrum disorder, and neurotypical individuals, where both are considered as gifted in mathematics (e.g. Casanova & Trippe, 2009; Treffert, 2009). Some such studies (e.g., Happé & Vital, 2009; Mottron, Dawson & Soulières, 2009) have indicated that the detection, integration and completion of patterns, and the requisite grouping processes, function in the negotiation of the phenomenological world, a tacit support for the arguments that any study of human cognition must be sensitive to the consideration of evolutionary processes (e.g., Calvin, 2004; Dehaene, 2004, 2009). In association with this pattern analysis is the ability to produce new material within the constraints of the integrated structure, a process which Mottron et al. (2009) refer to as creativity. In gifted individuals who are neurotypical, this integrated structure may be determined by automatic hierarchies that govern generalisation and memory processing through information loss and the limitation of the role of perception. Grandin (2009), a noted researcher who has autism and savant syndrome, has argued that the orientation towards pattern analysis that may be recognised as mathematics, as well as resulting from environmental interaction, may be due to differences in connectivity within individuals.

A better understanding of pattern analysis as a component of mathematics is, obviously, an important issue in understanding exceptional performance in mathematics. Snyder and associates (e.g., Snyder & Mitchell, 1999) have suggested, however, that the algebraic and algorithmic patterns and processes taught in mathematics may not correspond to the patterns and processes that they are designed to activate, and this is supported by Baars (1995) in proposing that humans use heuristic processes and analogies, rather than algorithmic processes, in dealing with patterns of environmental input. Although several capacities have been described for the brain—for example, problem-solving, decision-making and action control—Baars considers that one of the strengths of the brain, and the entire nervous system, may be in remembering and cross-analysing patterns observed from the real world, which is arguably an intrinsic mathematics capacity.

A flexible framework for cognition and giftedness

Although there is little in the way of consensus on how to accommodate information from differing studies of giftedness in mathematics, and giftedness in general, some of the parallels drawn between concepts within modern educational neuroscience and other disciplines have been used to erect a broader, more flexible framework within which to examine giftedness specifically and cognition more generally, (e.g., Woolcott, 2009a, 2009b, 2010a, 2010b). This flexible framework describes learning and memory processes in a broad sense in terms of information processing systems, and this is similar to the descriptions of human cognition and evolution in terms of natural information processing systems that have been used in some educational studies, such as those concerned with cognitive load theory (e.g., Sweller, 2007, 2010). This framework was developed from a consideration that learning and memory can be said to involve three temporally connected, but separable, stages in information flow:

1. environmental information input to or output from an individual;
2. processing of resultant information changes within the individual (information processing); and
3. changes in the observed state of the individual resulting from any such information processing.

In this flexible framework, the concepts of learning and memory have been generalised across both organismal and non-organismal structures, and all matter and energy described as information. All discrete organisations of matter and energy within the universe (in the sense of Gribbin, 1994) are described as information processing systems, with changes in information within such discrete organisations described as processing (Woolcott, 2010b, 2011). Learning and memory are described in terms of the overarching range of possibilities or potentialities of any change of matter and energy within such information processing systems where such change results from information input or output.

Within this framework, a human can be considered as a discrete matter and energy entity and human connectivity can be considered in terms of interactions with environment of the human information processing system and, as well, any designated structure within the human system can be considered also as a similarly discrete entity. On this basis human learning and memory can be described as a function of human connectivity with environment, as well as a function of connectivity within the central nervous system and, in particular, of neuronal connectivity within the brain. This framework supports the consideration separately of the differing aspects of human cognition within a dynamic system, and allows also a formalisation of the partitioning of cognitive structures, which is, in practice, a common method in dealing with learning and memory in cognitive psychology and the natural sciences (Woolcott, 2010b, 2011). For example, such dynamism operates, not only during storage of discrete information in long-term memory, but also in spatiotemporal sequencing of memories (Calvin, 2004; Postle, 2006) and in the linkage of emotions and chemical reward with learning and memory (Damasio, 1994; Le Doux, 2000; Panksepp, 1998). Neuronal patterns that develop with such intrinsic and dedicated flexibility act to adapt each human to a range of environmental inputs, including input classified as mathematics.

Since this framework supports explanations of cognition couched in terms of the interaction of component systems within the human organism, it supports the view that learned concepts are not necessarily uniquely subject-dependent. It is well known, that, even though some regions of brain activation may correspond to concepts described as, say, mathematics or reading, many common brain regions may be activated during processing of information in any subject (Dehaene, 2004; Geake, 2009a, 2009b). Lakoff and others (e.g., Lakoff & Núñez, 2000) have referred to such commonality of learning processes in terms of conceptual metaphors, as well as cross-domain mappings that preserve inferential structure and which are essential for linking conceptualisations generally, but which serve also for the linking of concepts in subject categories.

In considering a human individual as a type of universal information processing system, there may be differing component systems that may process information in different ways and over different time frames, but which may contribute to an assessable human performance, even if these systems sometimes overlap. The consideration of the human cognitive system as separable components suggests that it may be more useful to consider only those aspects of an individual's performance that may be viewed as superior, where those aspects result from components of that individual as an information processing system, rather than to consider that a student who has a superior performance in any one aspect is gifted in other ways as well. In this way giftedness may be conceptualised as the degree of expertise that an individual may have obtained in a culturally-valued knowledge domain, or the potential expertise in such a domain for which the individual may have an assessed performance, so long as it is recognised also that various components of the student's cognitive and related systems may contribute differentially to that expressed expertise. The consideration of separable information processing components may be useful also in examining aspects of giftedness such as motivation and emotion (e.g., Cotterill, 2001; Geake, 2009b).

An additional advantage of a flexible framework that supports a view of separable cognitive systems is that such a framework accommodates the concept of giftedness as the acquisition of knowledge in specialised domains in individuals that may otherwise have differences in cognitive connectivity, such as may occur in higher functioning in individuals within the autism spectrum (e.g., Casanova & Trippe, 2009; Grandin, 2006, 2009). Differences in connectivity between component systems, such as seen in neuronal hyper-connectivity and hyper-plasticity, may lead to the development of expertise, or giftedness, or may result in lack of expertise depending on what is being assessed (e.g., Casanova, 2010; Markram, Rinaldi & Markram, 2006). The flexible framework also accommodates the differences in abilities as explained by Haier and associates in their P-FIT model (e.g., Haier & Jung, 2008; Colom et al., 2009; Haier, 2009), since each component of the cognitive system, as described in the P-FIT model, can be treated effectively as a separate system in describing information transfer, storage, and recall.

Conclusion

Identification of giftedness, and the development of expertise based on that identification, may benefit from a broad approach that views human performance in a framework of interacting information processing systems, some of which have components in the environment external to the human organism. The framework outlined here indicates that education may have the potential to develop, through selective teaching to the system at large, any interacting systems that give rise to particular performances or abilities that are considered culturally valuable, whether these lie within, across or outside of the subject of mathematics or which link mathematics with other subjects. It may be necessary to re-evaluate our cultural mathematisation to more fully incorporate knowledge of brain processing that acts naturally across subject areas, particularly as it relates to the high level of expertise that is an expected result of gifted education.

This framework appears to offer reconciliation also of some of the disparate approaches that have been taken in studies of giftedness (see, for example, Perleth & Wilde, 2009) since the framework allows some comparison of such differing approaches through consideration of parallels that may be present between differing analogies and assumptions (e.g., Woolcott, 2009b, 2010b, 2011). Comparison and evaluation of such differing approaches may be useful in elucidating learning and memory processes to be used in education and teaching, including teaching of the gifted (Woolcott, 2009a, , 2010b). For example, the consideration that problem solving is the main function of learning and memory in the human interaction with environment (e.g., Grillner, 2003; Tonegawa et al., 2004) may be central to any educational strategy and, therefore, an important aspect of giftedness in mathematics. Gifted education, as is the case with education more generally, therefore, should develop such problem-solving ability through learning, in order that each individual maximise the potential for such interaction and the subsequent growth of contextually-linked information connectivity in long-term memory (for example, see Edelman in Sylwester, 1995).

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