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The Appearance of the Child Prodigy 10,000 Years Ago: An Evolutionary and Developmental Explanation

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Feldman and Goldsmith (1991) sought an evolutionary explanation of the child prodigy phenomenon. Following in this vein, a theory involving the evolution and development of the collaboration of working memory and the cognitive functions of the cerebellum is presented with commentary on Edmunds and Noel's (2003) report on a child's literary precocity. It is argued that (1) the evolution of working memory and the cerebellum within the increasing rule-governed complexity of culture may have produced the child prodigy within agricultural villages as early as 10,000 years ago, (2) in child prodigies, heightened emotional–attentional control in the central executive of working memory and modeled in the cerebellum is acquired in infancy through perceptual analysis (Mandler, 1992a, 1992b, 2004), and (3) this heightened emotional–attentional control begins in visuospatial processing, links visuospatial and language processing in working memory (Vandervert, in press), and initiates and accelerates a positive feedback loop with the cerebellum in a specific knowledge domain. It is concluded that the working memory–cerebellar approach provides an evolutionary and developmental explanation of the child prodigy and strongly supports Edmunds and Noel's visuospatial–high verbal ability explanation.

Keywords: cerebellum, giftedness, working memory

Child prodigies are extreme instances among gifted children where an adult level of skill in a particular domain of knowledge or performance is achieved by age ten (Feldman and Goldsmith, 1991; Winner, 1996). In their analyses of six child prodigies Feldman and Goldsmith found the accelerated learning so remarkable they felt it must have a deep evolutionary explanation. In the last section of their book they devoted a lengthy chapter to asking why, from an evolutionary standpoint, the child prodigy would occur in the first place. Feldman

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and Goldsmith thus set the stage for addressing ultimate questions about the place of the child prodigy phenomenon in the evolution of the human brain and mind. However, at the time their book was written solid evidence concerning the evolution of the neurophysiology of the human brain, human culture, and the human family that would allow the identification of mechanisms that might be at play in the child prodigy, had not yet become available.

In the same year Feldman and Goldsmith's child prodigy book was published, Leiner, Leiner, and Dow (1986) proposed that the evolutionarily newest parts of the cerebellum might accelerate information-processing in the cerebral cortex and thus contribute to the skillful manipulation of ideas:

> It has often been remarked that an explanation is required for the threefold to fourfold increase in the size of the cerebellum that occurred in the last million years of evolution (Washburn and Harding, 1970). If the selection pressure has been strong for more cerebellum in the human brain as well as for more cerebral cortex, the interaction between the cerebellum and the cerebral cortex should provide some important advantages to humans.
>
> Because the cerebellum is traditionally regarded as a motor mechanism (Holmes, 1939), these cerebrocerebellar interactions are usually thought to confer [only] a motor benefit on humans, such as increased dexterity of the hand (Tilney, 1928). But . . . a detailed examination of cerebellar circuitry suggests that its phylogenetically newest parts may serve as a fast information-processing adjunct of the association cortex and could assist this cortex in the performance of a variety of manipulative skills, including the skill that is characteristic of anthropoid apes and humans, the skillful manipulation of ideas. (p. 444)

Since this was originally written, the study of the collaborative cognitive functions of the cerebellum, including the attentional control and finer optimizations of language and working memory, has become a broad and indispensable part of the cognitive neurosciences (Ackerman, Mathiak, and Ivry, 2004; Blackwood, Ffytche, Simmons, Bentall, Murray, and Howard, 2004; Cabeza and Nyberg, 2000; Chávez–Eakle, Graff–Guerrero, Garcia–Reyna, Vaugier, and Cruz–Fuentes, 2007; Chein, Ravizza, and Fiez, 2003; Desmond and Fiez, 1998; Imamizu, Higuchi, Toda, and Kawato, 2007; Ito, 1993, 1997, 2005; Kelly and Strick, 2003; Leiner, Leiner, and Dow, 1989; Middleton and Strick, 2001; Ramnani, 2006; Schmahmann, 1997, 2004; Thach, 1996; Vandervert, Schimpf, and Liu, 2007).

Purpose

"The skillful manipulation of ideas" (Leiner et al.'s above quote) in all domains of knowledge is clearly the story of human *working memory*.[1] Vandervert (2003)

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[1]It is widely agreed among leading researchers who study the topic that working memory consists of three interrelated processes, a central executive (which governs *attentional control* for updating task-relevant information, switching back and forth among tasks, and inhibiting automatic but inappropriate responses), and two central executive slave systems, viz., a speech

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and Vandervert, Schimpf, and Liu (2007) argued that since the components of working memory must undergo constant repetition-rehearsal to maintain and update information in immediate awareness (Baddeley and Logie, 1999; Cowan, 1999; Goldman–Rakic, 1992), cognitive functions of the cerebellum must continuously accelerate and refine *all* aspects of working memory. Vandervert et al. therefore further proposed that, indeed, the cerebellum serves as a fast information processing adjunct to the skillful manipulation of ideas, but that this manipulation of ideas is specifically in the form of working memory. Following this contention, it will be argued below that the collaboration of the cerebellum and working memory is the basis of the accelerated learning and other characteristics of the child prodigy.

In the vein of Feldman and Goldsmith's (1991) expressed desire to find an evolutionary explanation of the child prodigy phenomenon, the purpose of this article is to examine the child prodigy from the perspective of the evolution of the collaboration of working memory and the cognitive functions of the cerebellum, including a proposal for why child prodigies occur in the first place. In addition to placing classic characteristics of the child prodigy in this new light, the role of the cerebellum in the transition from the visuospatial world of infant to the linguistic world of the child. Part and parcel to this examination, a brief discussion of a unique developmental window for learning in children is included. To help elucidate the processes of working memory and the cerebellum in these contexts, examples from a case study of a child prodigy will be included. For this purpose commentary from the sketch of a study of the considerable literary output of a precocious boy named "Geoffrey" (Edmunds and Edmunds, 2005; Edmunds and Noel, 2003; Noel and Edmunds, 2007) will be used.

Geoffrey exhibited the three classic characteristics of gifted children and child prodigies suggested by Feldman and Goldsmith (1991) and Winner (1996). First, there is earlier than normal, accelerated learning progress in some domain of knowledge or performance. Edmunds and Noel (2003) reported that Geoffrey did not do significant writing until Christmas when he was just over 5 years old. By the time Geoffrey was 6 years 1 month old, he had produced between 1,600 and 1,900 pages of writing. Over the course of the year and hundreds of pages the sophistication and level of thinking in Geoffrey's writing increased dramatically. Second, the child prodigy's accelerated learning

loop, and a visual-spatial sketchpad (Baddeley and Logie, 1999; Cowan, 1999; Miyake and Shah, 1999). Through the central executive, working memory functions are integrally associated with long-term memory (Miyake and Shah, 1999). Goldman–Rakic (1992) characterized working memory as the ongoing experience of thought: "The combination of moment to moment awareness and instant retrieval of archived information is what is called working memory . . ." (p. 111).

is self-directed. Geoffrey's great volume of literary work involved a dedicated one to 3 hours a day of self-directed writing; he had a "dogged persistence to satisfy his need to fully understand what he encountered or knew and then to express what he knew through writing . . . . He had a crystal clear determination of purpose" (Edmunds and Noel, 2003, p. 192). Winner (1996) referred to this strong, internally driven determination in child prodigies as "an insistence to march to their own drummer." Third, the child prodigy exhibits what Winner (1996) called "a rage to master" the domain of knowledge or performance. Geoffrey's focus of attention could last for several hours at a time in "quiet purposefulness guided only by his penchant for knowing" (Edmunds and Noel, 2003, p. 192).

Finally, it is important to note that Edmunds and Noel reported that Geoffrey's sudden explosion of literary precocity at age 5 was preceded at age four by all the signs of a visual–spatial precocity. Very early in childhood Geoffrey would ask his parents to draw pictures for him. He would be adamant for them to draw the pictures with realism, the way the scene really looked. This quickly grew into an extraordinarily strong visual–spatial fascination:

> Another demonstration of his early visual acuity and sense of proportion was his 8-month saga of his ever-evolving bedroom model of the city of Montreal, built out of cardboard boxes and a variety of toys and stuffed animals at age 4. His mother and father recollected that Geoffrey would look at it for hours and talk to himself about his "rearrangements of the buildings and stuff into the look that he wanted." I verified with Geoffrey that this model was not a replication of a photograph or postcard, it was his visual representation of Montreal as he saw it in his mind's eye. (Edmunds and Noel, 2003, p. 187)

Due to the large number of well-orchestrated, quality illustrations which were included in Geoffrey's first book, the book he started at Christmas, Edmunds and Noel contended Geoffrey's "abstract visual reasoning" (2003, p. 193) was a main complementary driver, along with his high verbal intelligence, behind his literary precocity. Within the theory presented in this article, it is proposed that the accelerated learning and other characteristics of child prodigies develop during infancy from the likewise complementary visual–spatial and linguistic components of working memory as contexted in emotional sensitivity. This developmental process will be revisited in more detail below.

Why Child Prodigies Exist in the First Place

The Accumulation of Rule-Based Knowledge and the Expansion of the Cerebellum

The evolutionary connection between working memory's "skillful manipulation of ideas" and the cognitive functions of the cerebellum first proposed by Leiner, Leiner, and Dow (1986) is particularly fascinating in regard to what perhaps are the earliest cultural signs of the child prodigy's often-reported penchant for rule-governed, performance-layered bodies of knowledge (Feldman and Goldsmith, 1991, chap. 4; Winner, 1996). Anthropologist Anne Weaver (2005) conducted an exhaustive study of how the dramatic expansions of the cerebral cortex and cerebellum co-evolved over the last two million years. Weaver's careful analysis revealed a surprising expansion in the cerebellum about 10,000 years ago during the early Holocene period — she found that at that particular time, the ratio of cerebellum to cerebral cortex shifted toward relatively more cerebellum. Following the suggestion of Leiner et al. that the cerebellum functions as an adjunct for the skillful manipulation of ideas, Weaver argued that this increase in the size of the cerebellum occurred because it "streamlined neocortical networking by providing the infrastructure for *rule-based* [italics added], procedural organization of sequential operations across many cognitive domains in response to cultural pressures" (2005, p. 3579). Although Weaver did not address reasons for the increase in cultural pressures 10,000 years ago, it is suggested that rule-based forms of knowledge became more prevalent with tasks and opportunities (in regard to both children and adults) associated with the establishment of relatively stable societies of the first agricultural villages which apparently emerged with early Holocene climatic warming (Gupta, 2004; Wilcox, Buxo, and Herveux, 2009).

Rule-based knowledge (for example, mathematics, music, language) is highly significant in descriptions of the accelerated working memory capacities of modern day child prodigies (Edmunds and Noel, 2003; Feldman and Goldsmith, 1991; Winner, 1996). Vandervert (2007, in press) pointed out that cerebellar streamlining is further demonstrated by the fact that working memory can be greatly accelerated in a variety of knowledge and performance domains through *deliberate practice* (Ericsson, 2002, 2003). Deliberate practice is defined by Ericsson as practice aimed toward constantly elevated levels of achievement or performance. Ericsson, Roring, and Nandagopal (2007) have provided convincing research evidence that deliberate practice may be the necessary and sufficient learning mechanism behind all forms of expert performance and the rule-based aspects of giftedness in children. Deliberate practice appears to be the essential learning mechanism at work in the three classic characteristics of child prodigies described by Winner (1996), viz., taking on progressive challenges, constant internal motivation, and relentless high focus of attention. Conditions of intensified cultural load such as those which had accrued in the relatively sedentary agricultural villages by about 10,000 years ago would have set the stage for opportunistic forms of intense deliberate practice among children, thus the likely emergence of the first child prodigies at that time.

In direct support of the above idea, anthropologists and psychologists have argued that a major reason for the evolutionary lengthening of childhood in humans over the last 2 million years was the advantage provided by the selection of windows of time for brain development necessary for the acquisition of increasingly large accumulations of knowledge and skills required for competent participation in the complexities of culture (Alexander, 1989; Flinn and Ward, 2005; Geary, 2007; Geary and Bjorklund, 2000). In other words, it takes a lot of experience-expectant brain maturation and related steps of practice to give the child a chance to get good at ever-intensifying cultural competencies. Since the evolutionary selection of the reciprocal expansions of working memory and the cerebellum coincided with (1) the evolution of larger and larger loads of cultural information (Weaver, 2005) and (2) the evolution of the lengthening of childhood (see Geary and Bjorklund, 2000 for a concise summary), the suggestion here is that human childhood is an evolved neurological framework selected for potentially huge variation in the downloading requirements of culture into the collaborative working memory-cerebellar system. The idea of specific childhood windows for intense levels of cultural downloading is supported by longitudinal neuroimaging of areas of brain growth (Thompson et al., 2000). Thompson et al. found that from ages three to 6 the frontal regions of the brain responsible for learning a variety of new behaviors developed rapidly, and that the growth rates of language areas experienced a general shut down of growth rate between ages eleven and 15, even though, after these ages, the children continued to take on a great number of new language and other new behavioral tasks. These findings are interpreted to indicate that the ages from three to 6 represent a window for the fundamental development of linkages among the central executive, the visuospatial, and language components of working memory. This period of rapid growth of working-memory visual–spatial and language linkages would likely carry forward any extremes in the earlier control of attention, for example, Geoffrey's fascination with visual–spatial information at age four, which apparently grew into his literary precocity which emerged at age five.

It is proposed that the existence of evolved human-specific windows in children for the downloading of extensive loads of cultural information and practices is a first orienting step in understanding why children have the information processing potential to, under certain circumstances, become child prodigies in the first place. While this provides a clue as to why child prodigies exist at all, there are of course additional aspects to this question. Just how does the cerebellum's streamlining of working memory account for the child prodigy's classic manifestations of profoundly accelerated learning? And, why do only a very few children actually become prodigies? Put another way, if evolution did select human childhood as a special window for cultural downloading, why are not all children prodigies?

How the Cerebellum Streamlines the Processes of Working Memory

It has been broadly known for decades that adaptive efficiencies occur in any bodily movements which are repeated (e.g., Dow and Moruzzi, 1958; Kornhuber, 1974). Through repetition, the cerebellum progressively learns short-cut anticipatory-control models which constitute the fastest, most appropriate, and efficient neural pathways for the execution of repeated bodily movements (Doya, 1999; Houk and Wise, 1995; Ito, 1997, 2005). This cerebellar streamlining (to continue with Weaver's apt term of facility) of bodily movement is why diligent practice is the key to, for example, sports and musical performance, especially at the highest levels. As to the streamlining of more purely mental processes, Ito (1993, 1997, 2005) proposed that both movement and thought could be controlled by the same type of cerebellar neural control mechanisms. Vandervert (2003) proposed that because all working-memory thought processes are continuously rehearsed in order to retain them in awareness, *all* thoughts, just as all bodily movements, are modeled in the cerebellum; cerebellar shortcut models for the execution of all thoughts are subsequently fed back from the cerebellum to working memory, thereby accelerating and improving (streamlining) the learning and manipulation of thought. The collaboration of working memory and the cognitive functions of the cerebellum is known to be richly served by cerebro-cerebellar (between the cerebral cortex and the cerebellum) feedback loops (Leiner and Leiner, 1997; Schmahmann and Pandya, 1997; Tamada, Miyauchi, Imamizu, Yoshioka, and Kawato, 1999).

The Development of Working Memory in the Infant

The classic characteristics of child prodigies (accelerated learning, self-directedness, and a rage to master a knowledge domain) indicate heightened attentional control. Cerebellar involvement in the regulation of attentional control has been described in some detail by Akshoomoff, Courchesne, and Townsend (1997). Akshoomoff et al. concluded that through learning of repetitive tasks the cerebellum plays an important role in the focus and shifting of attention in working memory and other cognitive tasks — the focus and shifting of attention are the key functions of the central executive (Baddeley and Logie, 1999; Cowan, 1999).

When do highly repetitive attentional tasks first occur in development? Mandler (1992a, 1992b, 2004) proposed that the infant's highly repetitive perceptual *meaning* analysis of its own bodily movement and of objects moving in the environment is distilled into image-schematic meanings which form the foundational basis of meanings for language.[2] Mandler (1992b) described the repetitive behavior of the early infant:

> Instead of merely "looking," the infant notices some aspect of the stimulus array, and recodes it into a simplified form that loses the details of what is being observed, but distils its meaning. The format of the representations that perceptual analysis produces is not propositional; rather, the theory proposes that the earliest meanings appear in the form of analogical representations called image-schemas. These early representations are part of the symbolic function in the sense that they are the meanings which symbols (gestures, images, or words) refer to or evoke. (p. 277)

It is suggested that in the distillation toward image-schemas suggested by Mandler, the cerebellum sends forward models from the infant's perceptual analytic activity to neocortical networking areas where they are *blended* (Imamizu, Higuchi, Toda, and Kawato, 2007) into image-schematic representations in working memory. Vandervert, Schimpf, and Liu (2007) argued that Mandler's sequence from repetitive perceptual analysis, then to foundational image-schemas, and on to the beginnings of language and speech gives a longitudinally connected operational birth to the *unique* attentional proclivities of the central executive of the infant's working memory. While perceptual meaning analysis leads to the formation of the same general categories of image-schemas in all infants, the *biases* of attentional control that become *embodied* within the central executive of a particular infant depends upon the infant's environment and its unique temperamental aspects of emotion regulation, e.g., attentional focus and inhibitory control (Goldsmith, Lemery, Aksan, and Buss, 2000). According to this view, the emotional sensitivity thought to be the basis of giftedness (Dabrowski, 1972) is "captured" in central executive attentional control of working memory and in this way emotional sensitivity gains its influence toward precocity. It should be noted here that, by definition, Mandler's image-schematic meanings embody attentional control. This is because perceptual "meanings" are distilled surrogates for emotional sensitivities and environmental circumstances that drive the intensity and patterning of what the infant "notices" (Mandler's above quote) — meanings are distilled emotional– attentional sensitivities in the form of visuospatial–linguistic concepts. Once learned as control parameters in working

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[2]The following abstract from Mandler (1992b) provides a synopsis of her position:

> The theory proposes that perceptual analysis redescribes perceptual information into meanings that form the basis of an accessible conceptual system. These early meanings are represented in the form of image-schemas that abstract certain aspects of the spatial structure of objects and their movements in space. Image-schemas allow infants to form concepts such as animate and inanimate objects, agents, and containers. It is proposed that this form of representation serves a number of functions, including providing a vehicle for simple inferential and analogical thought, enabling the imitation of the actions of others, and providing a conceptual basis for the acquisition of the relational aspects of language. (p. 273)

memory and in the cerebellum, these visuospatial–linguistic sensitivities determine the infant's future central executive attentional control.[3] In the cerebellum, these models of image-schematic meanings are transformed into streamlining neural networks for developing central executive attentional control in the foundational layer of a *hierarchical modeling architecture* (Haruno, Wolpert, and Kawato, 2003).[4]

Edmunds and Edmunds (2005) reported that Geoffrey began to exhibit high emotional–attentional sensitivity at age two. It is proposed that Geoffrey's emotional–attentional sensitivity drives his precocity, but only through the following steps: (1) the embodiment of emotional–attentional sensitivities in image-schemas, which are (2) streamlined in a cerebellar modeling architecture, and then (3) fed back to working memory central executive attentional control.

The Early Moments of the Child Prodigy's Domain Sensitivity

The foregoing arguments describe the cerebellar streamlining that begins uniquely with each infant's perceptual meaning analysis and is carried on into the attentional control principles behind the basic thought process, viz., the central executive of working memory. Findings that the cerebellum is involved in the (1) modeling of temporal–spatial aspects of perceptual prediction (Gao, Parsons, Bower, Xiong, Li, and Fox, 1996; Kawano et al., 1996; O'Reilly, Mesulam, and Nobre, 2008), (2) learning of attentional control (Akshoomoff et al., 1997), and (3) generation of internal speech (talking to one's self) and speech perception (Akermann, Mathiak, and Ivry, 2004) all strongly support this working memory–cerebellar theoretical extension of

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[3]Friedman et al. (2008) have provided convincing evidence that central executive attentional control is to a very great extent genetically determined. This would seem to argue against a learning explanation of attentional control. However, Friedman et al. take some effort to point out that their findings leave considerable room for the affects of training and various other environmental influences, and one can therefore assume, the affects of extremes in experience (p. 218).

[4]The purpose of the hierarchical cerebellar architecture (HMOSAIC) is to describe how movement and working memory processes predict and facilitate which movement and thought strategies will fit various contexts of unfolding circumstances (Wolpert, Doya, and Kawato, 2003). The HMOSAIC architecture runs from low-level dynamics of movements learned at any time (especially in infancy) with bi-directional connections up to all levels of abstraction, for example, the symbolic representation of language. Through repetition cerebellar models in this architecture "streamline" both mental and bodily performance and, at the same time, drive forward attentional control of the central executive of working memory. These models do this by feeding forward from the cerebellum to neocortical networks where they are blended with concepts already acquired (Imamizu, Higuchi, Toda, and Kawato, 2007), with continued mental processing looping back to the cerebellum and then toward more abstract and innovative thinking and so on.

Mandler's (2004) theory of conceptual development. Further, imaging studies by Imamizu, Kuroda, Miyauchi, Yoshioka, and Kawato (2003) revealed that, through learning, the cerebellum becomes modularized so that different knowledge domains acquire varying degrees of regulation. Thus, it is proposed that the earliest developmental moments of the child prodigy's domain-specific sensitivities can be found in central executive attentional sensitivities learned in the cerebellar hierarchical modeling architecture during the perceptual–analytic phase of infancy as described above.

It will be recalled from Edmunds and Noel's (2003) account that at a very early age Geoffrey developed high attentional interest in visuospatial arrays — he was adamant about having his parents draw pictures with realism, the way things really looked. And that by age four his high *central executive* (Geoffrey controlled the flow of pertinent information) attentional interest had elaborated into an "ever-evolving bedroom model of the city of Montreal" (p. 187). Moreover, Mandler's (1992b) hypothesized sequence from perceptual analysis and on into language-speech is supported by the fact that precisely at this stage Geoffrey would look at his model of the city of Montreal *"for hours and talk to himself about his 'rearrangements of the buildings and stuff into the look that he wanted* [italics added]' " (Edmunds and Noel, p. 187). This intense, eight-month-long saga of preparatory groundwork for Geoffrey's writing explosion (Edmunds and Noel, 2003) appears to reveal the working memory–cerebellar transition from Geoffrey's early central executive's high-attentional mostly visuospatial reliance to a more balanced visuospatial–speech loop reliance. This high attentional, balance of working memory's two slave components is attested to by the large number of quality illustrations that were part and parcel of Geoffrey's books. Edmunds and Noel's (2003) theoretical explanation of a synthesis of "high abstract visual reasoning [visuospatial sketchpad] combined with high verbal ability [speech loop]" (p. 193) in Geoffrey's literary work supports this point of view.

Moreover is the issue of creativity in Geoffrey's writing (Edmunds and Noel, 2003; Noel and Edmunds, 2007). I agree with Winner (1996) that little-c and big-C creativity are not the same thing. However, the processes which lead to both are integrally related. They are both the products of working memory and the streamlining processes of the cerebellum (Vandervert, in press; Vandervert, Schimpf, and Liu, 2007). They are both the products of the blending of neocortical models and cerebellar models which result in new syntheses (Imamizu, Higuchi, Toda, and Kawato, 2007). When blending involves only or mostly domain-specific, rule-governed models in working memory, the result is little-c creativity or novelty. On the other hand, if neocortical blending brings together more than one domain and involves open systems of knowledge, the result is always some degree of big-C creativity. By this definition, big-C creativity involves the blending of neocortical models at formal reasoning levels with cerebellar models at higher, more abstract levels of the cerebellar modeling architecture. According to this analysis, Geoffrey's writing appears to be in a transitional phase, moving toward big-C, domain-changing contributions.

The Role of the Cerebellum in the Generation of Language

There is another issue here with regard to Geoffrey's high verbal ability. In terms of cerebellar modeling architecture, it is proposed that the selective advantage of language evolution was that it enhanced the speed of control and the further decomposition and re-composition (Flanagan et al., 1999; Kawato, 1999) of working memory's flow of visuospatial imagery in socially and technologically (stone technology at first) adaptive ways. These are precisely the management properties of cerebellar models within the cerebellum's hierarchical control architecture described previously (Haruno, Wolpert, and Kawato, 1999, 2001; Imamizu, Higuchi, Toda, and Kawato, 2007; Imamizu, Sugimoto et al., 2007; Wolpert, Doya, and Kawato, 2003). Within this view it can be speculated that the selective evolution of language allowed visuospatial imagery (which we share to a great extent with other animals) to be analytically manipulated in working memory and to be directly communicated in finely articulated ways, a tremendous competitive advantage in any survival context — but this would also have greatly enhanced the internal silent speech dialogue necessary to learning (Ackermann, Mathiak, and Ivry, 2004). The foregoing scenario of the selection value of the decomposition and re-composition of visuospatial thought into both silent speech and overt language expression squares well with Noel and Edmunds' (2007) argument that "Geoffrey's work strongly suggests that he uses writing (i.e., language) as a tool for learning, as described by Vygotsky (1978), and that he also uses it to examine, in a very intentional manner, his own thinking" (p. 129).

What Drives the Child Prodigy Toward Higher Levels of Accomplishment?

Within the framework outlined above, as the child learns, the hierarchical modeling architecture of the cerebellum builds linkages between the earliest-learned elements of movements in the foundational level of the hierarchy on the one hand and symbolic representations of tasks learned in higher, more abstract levels of the hierarchy, on the other hand. Due to these linkages, which run bi-directionally up and down the cerebellar architecture, a variety of levels of thoughts, goals, or circumstances automatically can set in motion entire regimes of learned behavior and thought (Haruno, Wolpert and Kawato, 1999, 2003; Wolpert, Doya, and Kawato, 2003). This automatic sequential cuing effect, while especially structured in the case of rule-based domains of knowledge, also applies, through higher-level training and education, to open symbol systems. For example, in the everyday course of playing the piano, playing video games, in childhood sports, or even in the cases of creative artists or brilliant scientists like Albert Einstein (Vandervert, Schimpf, and Liu, 2007), the models that constitute the cerebellar modeling architecture have, through learning, come to set in motion sequences of anticipatory models that are appropriate to both rule-based and open-ended aspects of domains of knowledge. With each repetition of behavior or thought, rich feedback loops between the cerebellum and working memory (1) *automatically* adjust cerebellar models toward finer, more flexible levels of control and performance, and (2), at the same time, *automatically* adjust toward higher hierarchical levels of abstraction (Haruno, Wolpert, and Kawato, 1999; Ito, 1997, 2005). Thus, from the standpoint of both skill development (mentally and bodily) and continued motivation (the pleasure of discovery associated with higher levels of abstraction), the cerebro-cerebellar two-way circuitry acts as a self-propelling *positive feedback loop* of higher and higher self-directed attentional control, competence, and discovery. Alexander (1989) attributes the evolution of human intelligence to positive feedback loops associated with social competition, and Crespi (2004) describes several evolutionary positive feedback loops.

Once an attentional positive feedback loop such as that exhibited in Geoffrey's high emotional sensitivity at age two and continued in "his 8-month saga of his ever-evolving bedroom model of the city of Montreal" (Edmunds and Noel, 2003, p. 187) is initiated, the working memory–cerebellar collaborative circuitry becomes awash in an ever-rising sea of forward moving refinement and discovery. Edmunds and Noel reported that when Geoffrey's mother refused to draw suburbs for his model of Montreal, he drew them for himself. This "small" incident, obviously not small in Geoffrey's mind, began a "drawing areas of Montreal phase" which became an intense positive feedback loop. This positive feedback loop continued in his later production of 1,600 pages of story writing between ages 5 and six. The switch from the drawing phase to the story writing phase illustrates a developmental transition from mostly visual–spatial to largely linguistic processing.

The self-propelling positive feedback effect between the central executive of working memory and the hierarchical anticipatory modeling architecture of the cerebellum can be used to account for both Geoffrey's marching to his own drummer and his "rage to master." Geoffrey had his own "crystal clear determination of purpose" (Edmunds and Noel, 2003, p. 192). Geoffrey's clear and independent purpose appears to be the result of an entire chain of events: beginning with the affects of his temperamental biases on his perceptual meaning analysis, its embodiment in image-schemas in his working memory and their representation in his cerebellum, their resulting heightened attentional control in his central executive, and finally the development of the positive feedback loop between his working memory and cerebellum that collaboratively regulated forward moving higher-level goals. This developmental scenario would produce outcomes that would parallel point-by-point Winner's (1996) description of the self-directedness of child prodigies:

> The discoveries they make about their domain are exciting and motivating, and each leads the gifted child on to the next step. Often these children independently invent rules of the domain and devise novel, idiosyncratic ways of solving problems. (p. 3)

The same self-propelled positive feedback loop between working memory and the hierarchical cerebellar architecture that accounts for Geoffrey's self-directedness explains his rage to master, his "quiet purposefulness guided only by his penchant for knowing" (Edmunds and Noel, 2003, p. 192). Recall that, through the repetition of deliberate practice, the cerebellar architecture automatically adjusts toward higher levels of abstraction, goal formulation, and novelty. Noel and Edmunds' (2007) synthetic–analytic analysis of Geoffrey's writing provides abundant examples of this continuous higher-level cerebellar adaptive modeling.

Conclusion and Discussion

It appears that a working memory–cerebellar positive feedback loop effect may have been the main driver in the evolution of mental capacities and culture over the last two million years (Leiner, Leiner, and Dow, 1986; Vandervert, Schimpf, and Liu, 2007; Vandervert, in press). Alexander (1989) proposed that this positive feedback loop involved social competition among humans which accelerated the evolution of the human brain and the technology it produced over this period. By 40,000 years ago the acceleration of culture reached the proportions of a "creative explosion" (Pfeiffer, 1982). Ambrose (2001) described the explosion of artifacts typical of this Upper Paleolithic period:

> Of greater significance [than the blade-based stone technologies of this period] are ground, polished, drilled, and perforated bone, ivory, antler, shell and stone, shaped into projectiles, harpoons, buttons, awls, needles, and ornaments. Such artifacts are extraordinarily rare in MP/MSA [Middle Paleolithic–Middle Stone Age] sites but are a consistent feature of Upper Paleolithic (UP) and Later Stone Age (LSA) sites after 40 ka [40,000 years ago] . . . . Traces of more perishable materials, including string and woven fibers that may have been made into nets, ropes, bags, and clothing are also well documented. These innovations are among many that signify modern human behavior, including art, ornamentation, symbolism, ritual burial, sophisticated architecture, land use planning, resource exploitation, and strategic social alliances. (p. 1752)

Ambrose artfully characterized the awe modern humans have with the most recent installments of an ever-accelerated creative explosion: "A mere 12,000 years separate the first bow and arrow from the international Space Station" (p. 1752).

Weaver (2005) argued that by about 10,000 years ago rule-governed knowledge became so complex and abundant it taxed the capacities of human cerebrocerebellar networks, thus leading to higher burden on the streamlining functions of the cerebellum and expanding its size relative to the cerebral cortex. It is concluded that this great abundance of rule-governed knowledge, the expansion of the cerebellum, and the positive feedback loop between the cerebellum and working memory provided the conditions for the acceleration of working memory in high emotional–attentional children, the first child prodigies. This evolutionary and developmental explanation of the child prodigy helps us understand how a five or 10 year old child can be internally driven to achieve at the level of an adult, a phenomenon which is so remarkable and has such classic earmarks among child prodigies that Feldman and Goldsmith (1991) were convinced it must have an evolutionary explanation.

Edmunds and Noel's (2003) account of the literary production of the precocious child, Geoffrey, provides an excellent detailed basis for an analysis of his behavior based on the collaborative functions of working memory and the cerebellum. The working memory–cerebellar interpretation of Geoffrey's precocity strongly supports Edmunds and Noel's main theoretical suggestion that a complementary synergy between high verbal ability and high abstract visual reasoning best accounts for Geoffrey's exceptional literary production: Geoffrey's heightened central executive emotional–attentional control began in the visuospatial component of working memory and as more sophisticated language developed, the language functions were complementarily harnessed in a positive feedback loop of working memory–cerebellar adaptive efficiency. This high emotional–attentional positive feedback loop of working memory's central executive propelled accelerated learning, self-directedness, and a rage to master in Geoffrey — the cardinal characteristics of child prodigies.

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