Chapter 2
Child Prodigies: How Rule-Governed Skills and Social Cognition Are Optimized in the Cerebellum Through Deliberate Practice

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Fig. 2.1 The painting of Mozart

Portrait of the child prodigy Mozart while in his early trip to Vienna. Mozart is 6 years old in a costume given to him in 1762 at the Imperial Court in Vienna. Wolfgang Amadeus Mozart both played and wrote music for the piano by age 5. This portrait is in public domain and taken from https://commons.wikimedia.org/wiki/File:Wolfgang-amadeus-mozart_2.jpg

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On the Internet see also: http://blogs.biomedcentral.com/on-biology/2016/06/01/child-prodigies-1000000-years-silently-making/

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Abstract This chapter provides an explanation of child prodigies, notably in music, that is based upon collaborative cerebro-cerebellar functions that evolved with the progressive complexity of stone-tool making. Beginning with a description of the child prodigy Mozart, detailed examples of the role of deliberate practice by musical child prodigies are described. Within this framework, it is the purpose of this chapter to show how, during the last approximately 1.7–2.6 million years, (1) the brain's cerebellum and cerebral cortex progressively collaborated in the control of attentional focus in working memory; (2) how cerebellar sequence detection resulting in highly automatic (intuitive) forward control of cerebellar internal models led to the optimization of practiced movement, patterns of social-emotional behavior, and cognition in working memory; and (3) how, through cerebro-cerebellar *blending, constantly new components of working memory* originated that were adaptively structured into language, and, through neural plasticity, into the tonal working memory behind music. It is concluded that (1) such sequential or rule-governed working memory is highly accelerated in domain-sensitive children (child prodigies) through cerebro-cerebellar loops that exploded in size and information-processing capacity over the last 1.7–2.6 million years and (2) that with the rapidly expanding accumulation of culture, these cerebro-cerebellar loops may have first began producing child prodigies approximately 10,000 years ago.

Wolfgang A. Mozart: Child Prodigy

Mozart is perhaps the ultimate example of a seemingly inexplicable child prodigy. At age six (and thereafter through his early childhood) young Wolfgang Mozart startled and thrilled his audiences with his highly refined and quite broad variety of musical skills. Ericsson and Pool (2016) nicely captured the effect of his performances that began in 1762:

> We know from the historical record that at a very young age Mozart was impressing audiences across Europe with his playing of the harpsicord, clavichord and violin. Beginning when Wolfgang was six, his father took him and his sister on a multiyear tour across Europe. In Munich, Vienna, Prague, Mannheim, Paris, London, Zurich, and a number of other cities, the three Mozarts—Wolfgang, his father, Leopold; and his sister, Anna Maria—played exhibitions for the elites of the day. And of course little Wolfgang, his legs dangling from the bench and his hands barely able to reach the keyboard, was the main attraction. The Europeans had never seen anything like him. (pp. 211–212)

It is important to note that professor Anders Ericsson, the lead author of the book where this quote appeared, was internationally known for his studies of how extraordinary routines of practice led to extraordinary performers in all fields. We will return to his studies of what he called *deliberate practice* shortly.

Must-Read Quick Overview for All Students

As with Einstein in Chapter 1 of this reader, in this chapter evidence will be provided that strongly indicates that the child prodigy phenomenon most importantly involves the cerebro-cerebellar processing of working memory, which optimizes the development of all working memory-driven skills. However, since large numbers of child prodigies have been studied, we are able to delve into how normally adult-level skills can be optimized within the working memory of nearly anyone at a very early age. A case study of a young musical child prodigy named Tiffany Poon will be presented that shows details about how child prodigies develop—read this case study three times and be sure to pay close attention to its details. At the same time, keep these points in mind. While the development of child prodigies appears to be the result of a complex mix of genetics, parental encouragement, and practice, research indicates that practice is an absolutely essential ingredient in prodigy development. And, practice absolutely involves how the uniquely human cerebellum optimizes the ongoing processes in the cerebral cortex.

Introduction

Feldman (1993) defined the child prodigy as a child typically younger that 10 years old who performs at the level of a highly trained adult in a very demanding field of endeavor. However, child prodigies are not *performance automatons*. On the contrary, since they are often characterized by unique idiosyncratic problem solving, an independent "rage to master" (Winner, 1996), accelerated mental manipulation in working memory (Vandervert, 2016b, c), and, in musical prodigies, feelings of "flow" while performing (Marion-St-Onge et al., 2020), child prodigies are perhaps less robotic than others.

Rule-Governed Domains of Skill and Knowledge

Winner (1996) pointed out that:

> The more formal and rule-governed the domain, the more likely it is to yield gifted children [including child prodigies]. Mathematics and classical music, in which it is clear what needs to be mastered and how excellence can be recognized, are prototypical examples. (p. 5)

Winner described the term "rule-governed" as it typically relates to the organized structures of bodies or domains of knowledge such as in music, language, mathematics, chess, bridge, ballet, gymnastics, tennis, or precision skating. In this chapter, the rule-governed feature of such domains of knowledge is further and complementarily defined as derived from (1) sequence detection learned in the cerebellum (Leggio & Molinari, 2015a), (2) from forward control and prediction (Van Overwalle et al., 2019) learned in the cerebellum and both subsequently forwarded to appropriate areas of the cerebral cortex (Leggio & Molinari, 2015a, b; Vandervert, 2015, 2020a, b; Van Overwalle et al., 2019), and (3) ultimately, in evolution, from the precise rule-governed capacities of the cerebellum that were naturally selected during thousands of generations or the rigorous precision of the motor and mental sequences required by stone-tool making (Vandervert, 2018).

Purpose

Baddeley (1992) developed a model of working memory which describes its *operational features* that can be studied in a variety of laboratory settings. He proposed that working memory is a multicomponent "brain system that provides temporary storage and manipulation for complex cognitive tasks such as language comprehension, learning, and reasoning" (Abstract). Baddeley divided working memory into the following three subcomponents: (1) an attention-controlling system which serves as a "central executive," (2) a visual-spatial sketchpad which manipulates visual images within an ongoing flow of visual-spatial experience, and (3) a phonological loop which both *stores* and *rehearses* speech-based information.

The purpose of this chapter is to describe how, within the framework of the last million or so years of cerebro-cerebellar evolution, neural systems responsible for capacities for rule-governed cognition were added to working memory during tool-to-language evolution (Greenfield, 1991; Higuchi et al., 2009; Stout & Chaminade, 2012; Stout & Hecht, 2017; Vandervert, 2011, 2013, 2015, 2020a).

Vandervert (2019, 2020a, b) argued that these capacities for rule-governed mental processes where added to working memory *via* the adaptive selection of (1) a "tool loop" based on tool representations in the cerebellum (Imamizu & Kawato, 2012) and a hand-tool overlap in the cerebral cortex (Striem-Amit et al., 2017), (2) the simultaneous adaptive selection of the phonological loop (Baddeley, 1992; Marvel & Desmond, 2010, 2012), and, (3) finally through neural plasticity, the tonal loop within working memory (Koelsch et al., 2009; Schulze & Koelsch, 2012). Tonality is defined in this research as pitch, the lowness or highness of a tone depending on its vibrational frequency. The tonal loop is a primary basis for the processing and accumulation of musical knowledge and musical performance, including that of musical child prodigies (Williamson et al., 2010).

More on the Phonological Loop of Working Memory: The Natural Selection of New Sounds

Baddeley et al. (1998) argued that the primary function of the phonological loop (both in silent and overt speech) is to learn the sound patterns of *new* words and new syntactical sequences and thereby to mediate *language learning* (see p. 159). Baddeley et al. extended the phonological loop's function of learning new sounds to the *evolution* of language: "the primary purpose for which the phonological loop evolved is to store unfamiliar sound patterns while more permanent memory records are being constructed [in long-term memory]" (Abstract). Further, Baddeley and Hitch (2019) have argued how the phonological loop acts to combine sound information from multiple streams that may differ in either the speed of input or in the features coded. Accordingly, since it has been found that working memory is modeled in the cerebellum (Hayter et al., 2007; Marvel & Desmond, 2010, 2012; Marvel et al., 2019), following Schulze and Koelsch (2012), it is proposed in this chapter how a "tonal loop," for musical processing, evolved within the phonological loop through cerebro-cerebellar *blending* (Imamizu et al., 2007). Cerebro-cerebellar blending will be described in some detail in the later section of this chapter (see also Abdul-Kareem et al., 2011; Penhune & Steele, 2012; Steele et al., 2013).

The Evolution of the Human Cerebellum: Implications for the Child Prodigy

In their studies of six child prodigies, Feldman and Goldsmith (1991) found the pace of accelerated learning in child prodigies so remarkable; they argued that it must have a deep *evolutionary* origin. Feldman and Goldsmith thus set the stage for addressing fundamental questions about *neuropsychological mechanisms* that might accelerate learning in the child to adult levels by the age of 10. At the time their book was published, evidence concerning the evolution of the neuropsychology of the human brain that would allow the identification of those mechanisms had not yet become widely available. New, converging lines of evolutionary, behavioral, clinical, and brain-imaging research that would turn out to be perfectly suited to describing these mechanisms were just beginning to unfold.

A Game-Changing Breakthrough: The Cerebellum and Mental Processes

Over three decades ago, Leiner et al. (1986, 1989) published two landmark articles on how evolution has made human thought processes uniquely fast, complex, and efficient. Citing the fact that the small *cerebellum* at the back of the brain had increased in size three- to fourfold in the last million years of evolution, they proposed that the connections between the cerebellum and the cerebral cortex (cerebro-cerebellar connections) had evolved to increase not only the speed and skill of bodily movements but also the speed and skill of *mental processes*:

> 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* [italics added]. (1986, p. 444)

This indeed turned out to be a game-changing breakthrough. Leiner, Leiner, and Dow's watershed proposal spurred a huge amount of brain imaging research on the cognitive functions of the cerebellum and the cerebellum's massive two-way connections throughout the cerebral cortex—the 40 million nerve tracts between the cerebellum and the cerebral cortex are the most numerous in the brain, 20 times more than the two million that connect the eyes with the visual cortex (Leiner et al., 1993; Ramnani et al., 2006). Moreover, Lent et al. (2012) found that the human cerebellum contains over four times as many neurons as does the cerebral cortex, thus suggesting its huge roles in internal modeling, optimization, and automaticity of both behavior and thought. See Fig. 2.2.

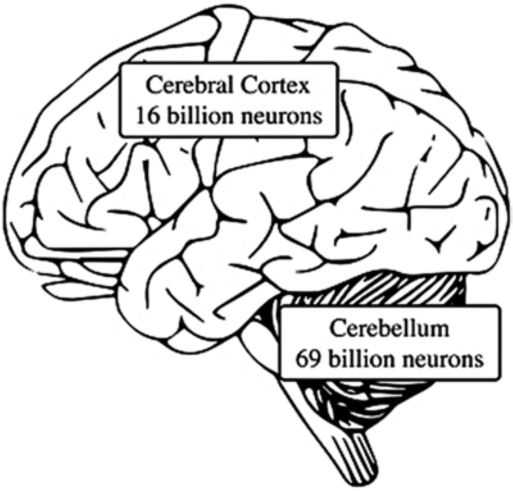

Fig. 2.2 Any repetitive movement or thought that is constantly improved (constantly optimized toward goals) and increasingly automated via more efficient, streamlined internal models by the 69 billion success-predictive neurons in the cerebellum (Lent et al., 2012). Cerebellar internal models consisting of these collections of neurons are sent to areas of the cerebral cortex where they are experienced and where blending with other such internal models may occur

The cognitive functions of the cerebellum proposed by Leiner, Leiner, and Dow have been overwhelmingly confirmed by imaging studies that have gone on to reveal not only cognitive but also social and emotional functions of the cerebellum (Adamaszek et al., 2017; Balsters et al., 2010; Balsters et al., 2013; Bostan et al., 2013, 2018; Desmond & Fiez, 1998; Dum & Strick, 2003; Imamizu & Kawato, 2012; Marvel & Desmond, 2010, 2012; Marvel et al., 2019; Murdoch, 2010; Ramnani, 2006; Schmahmann, 1997, 2013, 2019; Strick et al., 2009; Vandervert, 2020a, b; Van Overwalle et al., 2019). In this chapter, we will focus our attention on rule-governed domains of knowledge that are associated with the above-described skillful manipulation of ideas suggested by Leiner, Leiner, and Dow. Important: Revisit the Purpose section of this chapter for the definition of the term rule-governed.

Superfast Learning in Working Memory

There are two critically important principles in Leiner et al.'s (1986) above quote that lead to an explanation of the child prodigy's remarkable accelerated learning. First, "the skillful manipulation of ideas" constitutes what is now called *working memory* (Baddeley, 1992; Hautzel et al., 2009; Hayter et al., 2007). As will be seen below, without an accelerated development of working memory and its seamless relationship with performance, the child prodigy would not exist. Second, the "*fast information-processing"* in cerebro-cerebellar loops mentioned by H. Leiner, Leiner, and Dow is *automatically* initiated simply when an act (bodily or mental) is regularly *repeated* (e.g., Ito, 1993, 1997, 2005, 2008). As an act or thought is repeated, the cerebellum learns and optimizes its internal models that, when sent to the cerebral cortex, increase the speed, consistency, and appropriateness associated with that act or thought. Everyone is familiar with this seemingly "magical" transformations in speed and skill that take place as *practice* improves the dexterity of the hands along with the parallel dexterity of the thoughts controlling them in the learning of, for example, rapid, flawless executions of typing, piano playing, playing chess, and artistic sketching and sculpting.

How Can We Understand the Evolutionary Origins of Deliberate Practice That Leads Child Prodigies?

It is suggested that intentional control of rule-governed domains of skill and knowledge is derived from extreme movement and mental rule-based, precise control learned in the cerebellum through thousands of generations of repetition that occurred during progressive eras of stone-tool making. That is, the progressively refined capacities of attention toward sequence detection and forward (anticipatory) control were naturally selected during stone-tool making into cerebro-cerebellar circuitry. In this manner, the evolution of this highly precise, anticipatory control by autobiographical knowledge was learned in internal models in the cerebellum through intensive practice and provided the evolutionary basis for the efficacy of what is now called deliberate practice (deliberate on the part of components of one's concept of self within autobiographical knowledge).

Brain-based anthropologists (neuroanthropologists) Stout and Hecht (2017) referred to such stone-tool making as imitative or "high fidelity" social learning. As an example of this high fidelity social learning, they describe how it takes place (and took place between 2.6 and 1.7 million years ago) during the interaction between the learner and the teacher—that is, as we now know, how this interaction is socially modeled in the cerebellum:

> Knapping is a "reductive" technology involving the sequential detachment of flakes from a stone core using precise ballistic strikes with a handheld hammer (typically stone, bone, or antler) to initiate controlled and predictable fracture. This means that small errors in strike execution can have catastrophic, unreversible effects [*Thus shaping emotional-motivational states in the learner's autobiographical knowledge base—i.e., knowledge of past and future action/interaction sequences related to the self*[1]]. Experiments by Bril and colleagues have shown that fracture prediction and control is a demanding perceptual-motor skill reliably expressed only in expert knappers. Building on this work, Stout and colleagues found that even 22 mo ($\bar{x}$= 167 h) of knapping training produced relatively little evidence of perceptual-motor improvement, in contrast to clear gains in conceptual understanding.
>
> The key bottleneck in the social reproduction of knapping is thus the *extended practice* [italics added] required to achieve perceptual-motor competence. This requires mastery of relationships, for example between the force and location of the strike and the morphology, positioning, and support of the core, that are not perceptually available to naïve observers and cannot be directly communicated as semantic knowledge. Attempts to implement semantic knowledge of knapping strategies before perceptual-motor skill development are ineffective at best, and such knowledge decays rapidly along knapping transmission chains when practice time is limited, even if explicit verbal teaching is allowed. *For observational learning, the challenge is to translate visual and auditory information of another's actions to appropriate motor commands for one's own body. This may be accomplished by linking the observed behavior with preexisting internal models* [Stout and Hecht are referring here to internal models in the cerebral cortex and not in the cerebellum] *of one's own body and actions through associative learning and stimulus generalization* [italics added]. Novel behaviors are copied by breaking them down into familiar action elements (e.g., lift, turn, twist), matching these, and reassembling. (Stout & Hecht, 2017, pp. 7862–7863)

It is now known that what Stout and Hecht referred to as associative learning and stimulus generalization in the italicized portion immediately above are more accurately understood as the learning of internal models in the cerebellum. That is, while Stout and Hecht did not mention the cerebellum in their research, the implications of the 2.6/1.7 million years of socially driven adaptive focus and extensive practice by thousands of generations of learners for the evolution of social cognition mediated by the cerebellum are readily apparent (Ito, 2008; Van Overwalle et al., 2019). It is suggested that Stout and Hecht's above description of the rigors of stone-tool knapping provides the basis for Leiner et al.'s (1989) findings described above.

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[1] In the stone-tool making view of the evolution of the autobiographical knowledge/self, it is important to point out that autobiographical knowledge/self includes components which span the order of increasing adaptive optimization across the evolution of *Homo sapiens*, namely, spatial-visual, semantic episodic, and semantic conceptual components. See Martinelli et al. (2013) for a discussion of these components of autobiographical knowledge.

At least two important lines of evidence support the idea that Stout and Hecht's (2017) foregoing account of millions of years of precision, rule-governed practice during stone-tool making led to the evolution of the cerebro-cerebellar system that can in turn explain the likewise precise, rule-governed practice that drives the child prodigy phenomenon. First, in studying dysplasics (individuals born without hands), Striem-Amit et al. (2017) have described the evolution of an *innate* hand tool overlap (HTO) area in the occipital-temporal area of the cerebral cortex for the acceptance of tools into the hand:

> The HTO [hand tool overlap] would have emerged because of the potential advantage that accrues from the efficient processing of hands and tools as parts of a common (or closely intertwined), specialized system [tools being advantageous ancillaries]. This system, in turn, is connected to the dorsal, action-processing areas [parietal cortex] to allow quick and efficient shaping of hands to grasp and use tools [requiring both phylogenetic and ontogenetic cerebellar refinement]. Once evolved, this innately determined system would manifest itself ontogenetically even in the absence of any of the specific inputs, as in the case of the dysplasics, that originally contributed to the full usefulness of the pattern. (p. 4790)

Moreover, in subsequent research, Liu et al. (2020) found that the HTO has connections with the cerebellum (see Fig. 2.3). It is suggested that this innate hand-tool overlap evolved in the brain over at least the last million years of progressively

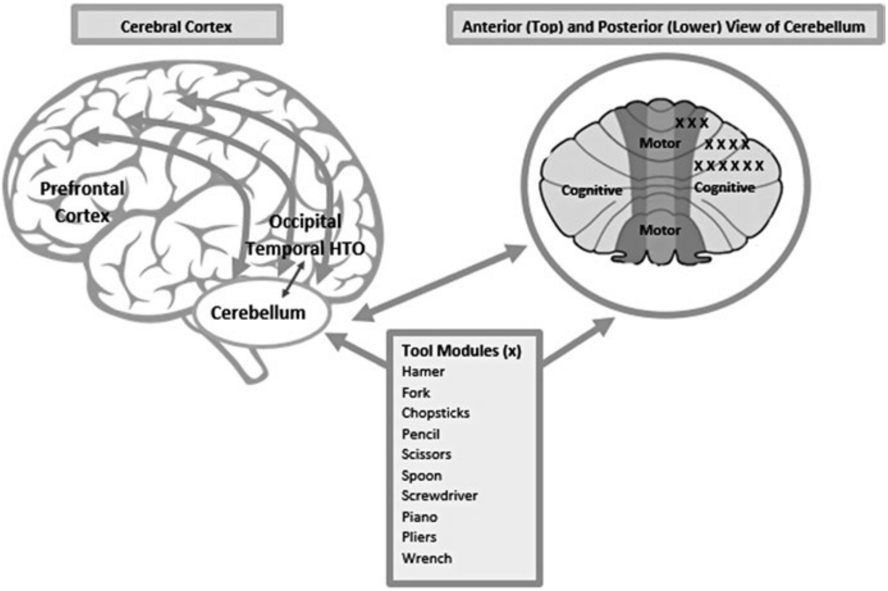

Fig. 2.3 The two-way arrows illustrated in the cerebral cortex depict in a simplified way the cerebellum's massive number of two-way connections throughout the cerebral cortex—about 40 million nerve tracts from the cerebral cortex carry input to the cerebellum and are the most numerous of such nerve tracts in the brain. This is 40 times more than the 1 million that connect the eyes with the visual cortex. The hand tool overlap (HTO) shown in the temporal-occipital area of the cerebral cortex has been found to be innate and to have connections with the cerebellum. The Xs shown in the anterior and posterior areas of the cerebellum show in a general way the locations of tool modularizations for both actual and imagined use of various tools, including the piano. (This figure was prepared by Kim Vandervert-Moe at kweathers@whitworth.edu)

refined stone-tool making and stone-tool use and the expansion of the social-cognitive cerebellum. *Second*, Higuchi et al. (2009) and Imamizu and Kawato (2012) found that both the *actual* and *imagined* use of tools are modularized, i.e., different parts of the cerebellum contribute to the use of different tools (see Fig. 2.3). They found specific modules for scissors, hammer, screw driver, and so forth. In addition, Parsons et al. (2005) found that, like tools, during actual or imagined use, the piano activates areas of the cerebellum (see list of tools in Fig. 2.3). These modularized models of tool and piano use (especially in their imagined use) are found largely in the newly evolved lateral cerebellar hemispheres which have expanded greatly over the last 1 million years. Since a variety of actual and imagined use of tools have been found to be learned in modules in the cerebellum, it is suggested that these modules are connected with the innate HTO. The cerebellum's dentate nucleus sends both actual and imaginary tool use models to the cerebral cortex where they are consciously experienced (Bostan et al., 2013).

Strong Parallels Across Precise, Repetitive Strikes in Stone-Tool Making, Social Cognition, and Autobiographical Knowledge Learning in the Cerebellum

Again, within the foregoing tool-making framework, it is suggested that the requirement during thousands of generations of social leaning of "precise ballistic strikes" where small errors "can have unreversible catastrophic effects" is the evolutionary origin of rule-governed cognitive and social processes. Within this framework, it is further suggested that controlling the acquisition of all domain-related skills and bodies of knowledge (music, chess, gymnastics, etc.) both in typical individuals and in child prodigies occurs in the cerebellum (The child prodigies' unique "rage to master" that sets them apart will be discussed below.). These rule-governed processes would occur through cerebellar internal models (models of ongoing processes internal to the cerebrum) based on sequence detection and forward control of social cognition and autobiographical knowledge as described by Leggio and Molinari (2015a, b) and Van Overwalle et al. (2019). Van Overwalle et al. described this overall forward control as follows:

> We hypothesize that the cerebellum acts as a "forward controller" of social, self-action and interaction sequences. We hypothesize that the cerebellum predicts how actions by the self and other people will be executed, what our most likely responses are to these actions, and what the typical sequence of these actions is. *This function of forward controller allows people to anticipate, predict and understand actions by the self or other persons and their consequences for the self, to automatize these inferences for intuitive and rapid execution, and to instantly detect disruptions in action sequences….* The cerebellum would be a "forward controller" that not only constructs and predicts motor sequences, but also takes part in the construction of internal models that support social and self-cognition. In this respect, the cerebellum crucially adds to the fluent understanding of planned and observed social inter-actions and contributes to sequencing mechanisms that organize autobiographical knowledge. Because the fundamental organization of the cerebellar circuitry is identical in

> many species adopting social behaviors, our hypothesis can also be valid throughout the animal kingdom. (p. 35)

Following Van Overwalle et al., autobiographical knowledge consists of cerebellar internal models consisting of sequences of memories of one's own life experiences and their meanings. Particularly relevant here to intentionally control rule-governed domains of skill and knowledge is the cerebellar sequence construction of the degree of success one has had with precision control in this or that skill and/or knowledge acquisition.

How the Cerebellum Encodes Practice into Unconscious Skills and Knowledge

Akshoomoff et al. (1997) provided early strong support for Van Overwalle et al.'s (2019) cerebellum-driven social cognition and autobiographical knowledge (including the conception of one's self). Specifically, they provided details on *how* and *why* the cerebellum encodes (learns) rule-governed sequences of internal and external events in the control and patterning of attention:

> The cerebellum is a master computational system that adjusts responsiveness in a variety of networks to obtain a prescribed goal [in Baddeley's (1992) working memory model, this is the *attentional control* of the central executive] (Courchesne, 1995; Courchesne et al., 1994). These networks include those thought to be involved in declarative memory, working memory, attention, arousal, affect, language, speech, homeostasis, and sensory modulation as well as motor control…We hypothesized that the cerebellum does this by encoding ("learning") temporally ordered sequences of multi-dimensional information about external and internal events (effector, sensory, affective, mental, autonomic), and, as similar sequences of external and internal events unfold, they elicit a readout of the full sequence in advance of the real-time events. This readout is sent to and alters, *in advance* [italics added], the state of each motor, sensory, autonomic, attentional, memory, or affective system which, according to the previous "learning" of this sequence, will soon be actively involved in the current real-time events. *So, in contrast to conscious, longer time-scale anticipatory processes mediated by cerebral systems, output of the cerebellum provides moment-to-moment, unconscious, very short time-scale, anticipatory information* [italics added]. (Akshoomoff et al., 1997, p. 592)

These unconscious, moment-to-moment anticipatory encoding processes of the cerebellum have recently been strongly supported in studies of perceptual analysis. Moreover, specifically in the case of piano practice, Lee and Noppeney (2011) have substantiated Akshoomoff et al.'s foregoing cerebellum-mediated encoding and temporal binding of sequences of multidimensional information. Specifically, they found the following:

> At the neural level, musicians showed increased audiovisual asynchrony effects and effective connectivity for music in an STS [superior temporal sulcus]-premotor cerebellar circuitry. Collectively, these results suggest that piano practicing provides more precise estimates of the relative audiovisual timings in music by fine tuning an internal forward model that maps from action plans of piano playing onto visible finger movements and concurrent piano sounds. (Lee & Noppeney, p. E1446)

Origin of the Prodigy's "Rage to Master"

Moreover, in accordance with Akshoomoff et al.'s (1997) above findings, especially related to arousal and affect, the cerebellum would control attention through functions of autobiographical knowledge that are key to the prodigy's unconscious (1) emotional concerns for weaknesses in their achievement of skills, (2) access to driving emotional history related to those weaknesses, and (3) nuances of musical skill associated with achieving the desired level of expertise (usually that of the teacher or of expert performers in general). It is suggested that, collectively, these three unconsciously driven drives constitute one of Winner's (1996) characteristics of child prodigies, the "rage to master." It will be shown below in the case study of child prodigy Tiffany Poon that this cerebro-cerebellar "fine tuning of internal forward models" was precisely what was taking place during her extensive practice when, beginning at age two, she "would imitate on her toy piano the orchestral and piano recordings she was listening to on her father's stereo system. Her parents report that she did this for many hours each week" (McPherson in McPherson & Lehmann, 2012, p. 43).

Cerebro-cerebellar Blending: A Four-Part Creative Mechanism in the Child Prodigy

Winner (1996) pointed out that as they rapidly advance in their skills, gifted children, including child prodigies, solve problems in "idiosyncratic (apparently intuitive) ways" (p. 102). She referred to this gifted-child idiosyncratic problem-solving as "little *c* creativity" as opposed to big *C* creativity, which is seen in adults after many years of work in their areas of expertise. We will return to this idiosyncratic little c creativity in more detail in a moment.

Imamizu et al. (2007) found that when confronting *new* situations, cognitive-manual skill routines and strategies learned in internal models in the cerebellum were *blended* in the prefrontal cortex and parietal regions of the cerebral cortex to negotiate the new challenges. Following Vandervert (2015), it is proposed that through idiosyncratic shifts of attention in work memory, such blending drives both little-c and big C creativity. Imamizu et al. argued that cerebral blending of multiple cerebellar cognitive-manual skill routines and strategies bestowed several tightly interrelated problem-solving advantages. These advantages include the following: (1) Interference between different learning epochs is reduced thereby enabling the rapid switching of sequential skilled behaviors. (2) Entirely new skill demands can be coped with by adaptively blending preexisting motor and cognitive primitives as multiple cognitive-manual skill routines and strategies. (3) Multiple cognitive-manual skill routines and strategies are blended *in proportion* to the requirements of the current new context. (4) Because blending is proportionate to the specific requirements of changing contexts, an enormous, perhaps limitless, repertoire of behavior can be generated even when the number of cognitive-manual skill routines and strategies might be limited. Through the child prodigy's extreme practice-driven shifts of attention, the combination of these four mechanisms means that an enormous number of new nuances whether of novel sound forms representing new words for language, or new *tonal information* underlying music can be mixed or blended within either/both old or/and new visual-spatial contexts. Cerebro-cerebellar blending appears to be the driver of the neural plasticity of rule-governed processes in working memory both in evolution and in the ontogenetic development of the musical child prodigy. This contention is strongly supported by "forward model mapping" found in cerebellar-premotor circuitry of practiced pianists which integrates (blends or binds) visual, auditory, and tactile information (Lee & Noppeney, 2011).

Gifted Children Including Child Prodigies Learn Intuitively More Than Typical Children Do

Strong support for the prominent role of such fine-tuning of cerebellar automaticity in the development of child prodigies, which Winner (1996) describes as extreme cases of giftedness, can be seen in the automatic or intuitive way gifted children process their problem solving skills. Because these skills are learned through copying and unconscious autobiographically initiated routines of deliberate practice, they are not freely open to conscious examination in conscious working memory:

> Gifted children—whether gifted in math, language, art, or music—learn faster and present information in their domain in an atypical way. Children gifted in math solve problems in idiosyncratic (apparently intuitive) ways, and they may thus have difficulty when forced to shift to formally established methods. Recall David [a math child prodigy discussed earlier in the book] when he was asked in school to write down in linear fashion the steps he used in solving a math problem. Children gifted in language simply see the way words should sound, and they do not have to sound them out bit by bit, using a deliberate phonetic strategy. Children who draw realistically use a figural strategy, drawing what they see without thinking about it much. When forced to think about the rules of unified perspective, say in a high school art class, they may have difficulty shifting to this more [traditional] conscious, conceptual, and rule-governed system. (Winner, 1996, p. 102)

Recall that Winner (1996) described child prodigies and extreme cases of gifted children. The idiosyncratic automaticity that is common to gifted children and child prodigies reveals a prominent role of the automaticity of all skills and knowledge that are learned in the cerebellum. The idiosyncratic learning of child prodigies is indeed reminiscent of Stout and Hecht's (2017) earlier description of the key bottleneck in stone-tool making. Namely, that extended individual practice was absolutely necessary and that semantic knowledge was a little or no help:

> The key bottleneck in the social reproduction of knapping is thus the *extended practice* [italics added] required to achieve perceptual-motor competence….Attempts to implement semantic knowledge of knapping strategies before perceptual-motor skill development are ineffective at best, and such knowledge decays rapidly along knapping transmission chains when practice time is limited, even if explicit verbal teaching is allowed. (p. 7862)

Is the stone-tool making strategy of extended practice the evolutionary key to understanding the child prodigy?

Encoding the Control of Attention and Its Synthesis Toward Constantly New Music in the Child Prodigy

Cerebellar *encoding* can explain how control of attentional focus and attentional shifting is learned along domain-specific lines (Akshoomoff et al., 1997). But how exactly, through practice, does this encoding become mixed and elaborated into specific complexes of moment-to-moment "architectural" structure of, for example, exceptional athletic or musical performance of the child prodigy? Ericsson and Roring (2008) provided the following example of such complex structures which must be learned by musicians:

> Similar to actors, expert pianists must memorize large amounts of information, namely scores of music, for their public performances. Also like actors, pianists must go beyond mere recall of the information, and must produce a pleasing musical experience [including the pianist's perceived intentions of the composer]. Chaffin and Imreh (2002) argue that the structure of a music piece possesses a natural hierarchy [of rule-governed information] of movements, sections, subsections, and bars that could serve to organize a set of performance (retrieval) cues in a retrieval structure. Examples of performance cues could include dynamics, tempo, use of pedal, and emotions to be conveyed during performance (the latter being the most effective in Chaffin and Imreh's analysis). (p. 368)

To understand how the cerebellar encoding of timing of attentional focus and attentional shifting can be orchestrated into such complex hierarchically structured *syntheses* of mental, movement, auditory, and emotional outcomes in the child prodigy, it is necessary to describe how the cerebellum and cerebral cortex collaborate in the *blending* of these rule-governed components in working memory.

Tools (and Musical Instruments) and the Phonological and Tonal Loops of Working Memory in the Cerebellum

Within Vandervert's (2018, 2020a) above interpretation of Stout and Hecht's (2017) description of stone-tool making as learning in the social cerebellum (Van Overwalle et al., 2019), tool-related cerebro-cerebellar circuits are richly connected in social cognition. The functions of these connections include (1) tool use (Imamizu & Kawato, 2012; Obayashi et al. 2002, 2007; Vandervert, 2018)), (2) language (Leiner et al., 1986, 1989); Vandervert (2020a, b), and (3) the phonological (speech) loop in working memory (Hautzel et al. (2009); Hayter et al. (2007); Vandervert (2020b)). Figure 2.3 contains a partial list of the 16 tools which Imamizu and Kawato have found to modularize in the cerebellar cortex. It appears that rule-governed processes in cerebro-cerebellar circuits underlie all of these cognitive activities

and are tied in with, among other cerebro-cortical areas, the prefrontal cortex (Balsters et al., 2013). Koelsch et al. (2009) and Schulze and Koelsch (2012) have proposed that the phonological loop also stores and rehearses tonal-based information for use in working memory (see also Williamson et al., 2010). The idea that the cerebellum evolved as a fast information-processing adjunct to the association cortex within the context of rule-governed tool, manufacture and use are strongly supported by the fact that the newly lateralized regions of the cerebellum readily modularize for both the actual and imagined use of tools (Imamizu & Kawato, 2012). It should be noted here that, as do tools, during the pianists' actual performances of a concerto by J.S. Bach, the piano was found to modularize in the cerebellar cortex (Parsons et al., 2005). In the eyes of the cerebellum, musical instruments are apparently "tools." It is suggested that the cerebro-cerebellar evolution of tool use was the origin of the availability of a phonological-tonal loop in working memory, an availability which underlies both our capacities for song and for the construction of music-related tools (pianos, violins, and so forth).

Modern Mozarts: A Case Study of a Musical Child Prodigy

While young Mozart's precocious musical abilities described at the beginning of this chapter are widely known and seemingly extremely rare, there are many musical child prodigies in modern times. We will now examine a brief case study of one of the more recent child prodigies. Subsequently, using the details of this case study, we will examine (1) the evolution of the cerebro-cerebellar system that made the rapid, precise learning of child prodigies possible and (2) how focused attention by the cerebellum and deliberate practice played key roles for Tiffany Poon, the very young girl described in the case study.

McPherson and Lehmann (2012) described the early and extreme practice regimen of the musical prodigy Tiffany Poon (see also www.tiffanypoon.com):

> *Things began at about two years of age*, [italics added] when Tiffany would often sit at a toy piano and try to imitate melodies that she heard on the TV and hi-fi. In preference to going to a toy shop, she would accompany her father to purchase piano recordings which they would listen to on his stereo. At the age of four and a half, Tiffany began to take formal piano lessons, and after three years of learning was *practicing up to three or even four hours per day* [italics added], and capable of performing Grade 8 Associate Board repertoire. During the early stages of development, her mother reports sitting with her daughter and playing games that helped focus the child on repetition and mastery. For example, the mother would challenge Tiffany by saying: 'Can you play that scale again five times correctly?' 'Can you play it 10 times correctly?' Now, can you play it 50 times correctly?' …
>
> From the very beginning, there appears to have been a distinct difference between Tiffany's learning agenda and those of her teachers. She displayed *superb self-regulatory skills* [italics added] for her age. Over weeks she listened extensively to CD recordings of piano repertoire before choosing those works that she wanted to learn. Most important, before physically attempting to master work, Tiffany would typically acquire *a clear mental image of the piece through repeated hearings of the music (and using various recordings)* [italics added]. This strategy is quite different from how most teachers typically proceed, namely from symbol to sound. Her rage to master was not related to the technique of playing the piano but rather what needed to be done in order to master the desired repertoire that she already knew [by means of her "clear mental image" of the piece] from recordings. (McPherson & Lehmann, 2012, pp. 42–43)

The extreme focus of attention and practice seen in the case of Tiffany Poon has been studied extensively by Ericsson (1990), Ericsson (2006), Ericsson et al. (1993), Ericsson and Roring (2008), and Ericsson et al. (2007). These researchers refer to the child prodigy's form of practice as "deliberate practice." In deliberate practice, much of which is solitary practice, the learner focuses attention on weak aspects of their performance that are related to the teacher's level of performance. The learner's specific degree of ability to focus attention upon their own weaknesses would be a function of his or her autobiographical knowledge as described by Van Overwalle et al. (2019). Here, autobiographical knowledge consists of cerebellar internal models consisting of sequences of memories of one's own life experiences and their meanings. This focus of attention toward goal attainment has been found to be controlled by anticipatory (forward control) functions of the cerebellum (Akshoomoff et al., 1997). We will return more on how the cerebellum is involved in the learning of the autobiographical knowledge and forward (anticipatory) control in the next section.

Postscript: Is the Piano Really a "Tool?"

Tools can be defined as any objects or mechanisms that are used to achieve a goal. To further elucidate the concept of tools, it is helpful to consult Sigmund Freud's description of tools that fits nicely into the cerebro-cerebellar context of this discussion. In describing the origins of culture, Freud proposed that the evolution of the technological aspects of culture has amounted to advantageous amplifications of the functions of (1) our muscles and movements and (2) the perceptual and working memory functions of our brains:

> With every tool man is perfecting his own organs, whether motor or sensory, or is removing the limits to their functioning. Motor power places gigantic forces at his disposal, which like his muscles, he can employ in any direction; thanks to ships and aircraft neither water nor air can hinder his movements; by means of spectacles he corrects defects in the lens of his own eye; by means of the telescope he sees into the far distance; and my means of the microscope he overcomes the limits of visibility set by the structure of his retina. In the photographic camera he has created an instrument which retains the fleeting visual impressions, just as a gramophone disc retains the equally fleeting auditory ones; both are at bottom materializations of the power he possesses of recollection, his memory. With the help of the telephone he can hear at distances which would be respected as unattainable even in a fairy tale. Writing was in its origin the voice of an absent person. (1930, p. 37)

Freud could easily have added musical instruments, including of course the piano to his list, as they represent basic emotional aspects of the brain, and of the tonal aspects of working memory—musical instruments amplify both our personal and social group well-being. How do these amplifications occur? It is suggested that through stone-tool making, the cerebro-cerebellar system evolved to design (through the blending of internal models) and manipulate material object configurations that efficiently achieved goals (Akshoomoff et al., 1997). Such design innovations and discoveries gave rise to ever-new horizons of goals. In this regard, had Freud conceived the foregoing view of how these various tools amplify human capacities, not in the late 1920s but in today's world, he would no doubt have greatly expanded the technological amplifications of brain functions greatly. Surely, he would have greatly expanded his mentions of memory and writing to include the problem-solving of everyday computers, voice synthesizing and recognition, and the manipulation of language and mathematical storage in, for example, iPhones.

In all of these examples of tools, Freud is saying something quite simple: The advantages bestowed by the technological framework of culture are direct amplifications of the motor, sensory, and higher cognitive functions of the brain and the bodily systems it controls. That is, both the advent of culture was and cultural advances are naturally selected for because they place more physical, sensory, and cognitive power and control (collectively, the capacity for adaptation) at the disposal of humans.

Discussion and Conclusion

Leading gifted child researchers noted that child prodigies (extreme cases of giftedness) most often excel in rule-governed domains (Winner, 1996). Here, this key point is coupled with Feldman and Goldsmith's (1991) argument that the remarkableness of the accelerated learning of child prodigies suggests that it must have had an evolutionary basis. In this chapter, *the evolutionary origins of rule-governed mental and behavioral capacities are attributed to the fact that stone-tool evolution, also rule-based, led to the natural selection of a rule-governed working memory, including tonal working memory, the basis of musicality.* Specially, it is now widely accepted that rule-governed stone-tool evolution was the precursor or perhaps a concomitant of language evolution (Barton & Venditti, 2014; Greenfield, 1991; Holloway, 1969; Leggio & Molinari, 2015a, b; Stout & Chaminade, 2009, 2012; Vandervert, 2011, 2013, 2018, 2020a, b). Following these findings, it is proposed that during approximately one and half million years of stone-tool evolution, rule-governed force dynamics of action were adaptively selected into (1) the social cognition (Van Overwalle et al., 2019) required of tool manufacture and use and (2) into the phonological loop, and, (3) through neuroplasticity, dating back 50 to 60 thousand years, the tonal loop of working memory which underlies musicality. An abundance of imaging evidence has shown that this new powerful working memory is mediated in the brain by the recent (during the last million to one and half million years) great yoked expansions of the cerebellum and the cerebral cortex (Leiner et al., 1989, 1993; Stout & Hecht, 2017). Following these findings, Vandervert (2016b) proposed that the accelerated learning of the child prodigy is produced through perceptual-motor, emotional, and working memory processes which have been found to be the result of the constant collaboration of the cerebellum and the cerebral cortex (Adamaszek et al., 2017; Akshoomoff et al., 1997; Barton & Venditti, 2014; Ito, 2008; Van Overwalle et al., 2019; Van Overwalle & Mariën, 2016). This collaboration is based upon highly focus attention during the deliberate practice learning of rule-governed sequences learned in the cerebellum at an unconscious level and subsequently sent to the cerebral cortex in the execution constantly optimized performance (Akshoomoff et al., 1997; Ito, 1997, 2005).

In sum, the adaptive intensive practice necessary to the evolution of the precision sequential skills in stone-tool making can be argued to have led to the cerebro-cerebellar basis of the equally intensive practice necessary to the achievement of the accelerated learning of the child prodigy. Within this stone-tool making-child prodigy homology, it seems that the child prodigy can reasonably be seen as a mirror image of the thousands of generations of the intense practice adaptively selected into the cerebro-cerebellar system but played out in quick time. This view offers an explanation of the child prodigy that coincides with Feldman and Goldsmith's (1991) contention cited early in this chapter that the child prodigy is so remarkable, it must have deep evolutionary origins. Both the child prodigy and the 2.6 to 1.7 million years of stone-tool making that led to the rule-governed wisdom of *Homo sapiens* are quite remarkable.

Psychology Achieves the Impossible: Understanding Child Prodigies—Essay questions

1. Describe the roles (at least two) of the cerebellum in producing child prodigies.
2. How did Feldman define child prodigies?
3. Earlier in this chapter, Winner (1996) pointed out that "Children gifted in math [and child prodigies in math] solve problems in idiosyncratic (apparently intuitive) ways, and they may thus have difficulty when forced to shift to formally established methods." Use your answer to the first question above to explain why this might be so.
4. How are the findings of neuroanthropologists Stout and Hecht (2017) important to understanding the ancient origins of the child prodigy?

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