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The New Revolution in Psychology and the Neurosciences

With an Interdisciplinary Approach to the Role of the Cerebellum

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ISBN 978-3-031-06092-2 ISBN 978-3-031-06093-9 (eBook)
https://doi.org/10.1007/978-3-031-06093-9

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Preface

What if you could regulate your thoughts and social relationships as efficiently as you do your arms and legs? The chapters of this book provide recent and solid neurocognitive evidence that over the last million and half years the human brain has evolved to do precisely that. In particular, the cerebellum is an integral part of complex brain machinery which has allowed humans to adapt to movement and mental demands occurring during daily life.

A Revolution: The Cognitive and Social Functions of the Cerebellum Played a Key Role in the Rise of Homo *sapiens* and the Ongoing Advancement of Culture

Historically, psychologist and neuroscientists believed that the cerebral cortex manufactures the unique mental and social capacities of human beings. However, a preponderance of brain-imaging evidence now shows that the cerebral cortex, while the seat of our everyday experience (notably in working memory), is not solely responsible for *producing* our amazing capabilities. Rather, the achievements that mark humans as Homo *sapiens* now appear to be heavily influenced by the constant communication between the cerebral cortex and the cerebellum. It is now understood that during a million and half years of the evolution of stone-tool making,[1] the achievements of early humans that became Homo *sapiens* were modeled and refined (optimized) largely through the involvement of the *cerebellum* which increased three- to fourfold in size and expanded its connectivity with the cerebral cortex during this time. This book was written to reveal how through an iterative optimization

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[1] See, for example:

1. Ambrose S. Paleolithic technology and human evolution. Science. 2001; 291: 1748–53.
2. Stout D, Hecht E. The evolutionary neuroscience of cumulative culture. PNAS. 2017;114(30):7861–8.

of experience within the cerebral cortex the cerebellum has, on the one hand, been critical to the evolutionary development of culture, technology, mathematics, language, social thought and behavior, creativity, and extremely high skill levels in all areas from sports to mathematics and art, and to many psychological and movement disorders on the other. These new discoveries represent a new revolution in psychology and the neurosciences.

Accordingly, the chapters of this book were written in a way to reveal how these optimization processes led to Einstein's great discoveries, the amazing abilities of child prodigies, mathematical discovery, culture itself, how working memory works, and what is behind many cognitive and affective disorders. At the same time, the fundamentals of this discovery process are repeated in different contexts of accomplishment in each chapter. This repetition is meant to engage the discovery process in the reader's mind, thus carrying their understanding to increasingly higher levels.

With more than 60% of all neurons in the brain and its high connectivity with the cerebral cortex, the cerebellum can now be seen as the brain structure which tunes all aspects of human behavior, from simple motor acts to thought, ideas, and high order concepts. The cerebellum is intimately linked to executive control which is the ability to orchestrate cognitive tasks to achieve specific goals. Through repetition and error corrections toward optimization, the cerebellum adjusts behavior and thought to make it more efficient. Its key role in predictions and anticipations makes the cerebellum a unique component of the fantastic brain machinery of our species.

Charleroi, Belgium Mario Manto
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The young field of the cognitive neuroscience of the cerebellum has matured. The clinical implications have become increasingly apparent, and the fundamental questions have deepened. There is now a more holistic and realistic view of the cerebellum and its necessary and unique contribution as an integral node in the distributed neural circuits subserving human behavior across all domains. (Schmahmann JD. The cerebellum and cognition. Neurosci Lett. 2019 Jan 1;688:62–75. https://doi.org/10.1016/j.neulet.2018.07.005. Epub 2018 Jul 8. PMID: 29997061.)

Jeremy D. Schmahmann, Department of Neurology, Massachusetts General Hospital and Harvard Medical School

About the Book

Evidence from anthropology and brain-imaging have shown that during a million and half years of the evolution of the repetitive actions required in stone-tool making, the cerebellum increased greatly in size, especially its lateral portions. Cerebellar growth was accompanied by expanded connectivity with the cerebral cortex and enhanced cognitive and social functions. This evolutionary process occurred in the cerebellum continuously as its optimization and automaticity of cognitive, social, and emotional functions were adaptively selected in the cerebral cortex. Communication between the cerebellum and cerebral cortex over time led to improvements toward problem solving in working memory to eventually produce innovation, creativity, and new levels of cognitive efficiency. It is a major assertion of this book that such progress directly led to performance enhancements that result in advances in science, technology, engineering, and math, high levels of skill in child prodigies, and the advance of culture in general.

A New Revolution in Psychology and the Cognitive Neuroscience

All of these higher performance levels occurred through multiple *positive feed-back loops* running parallel between the cerebellum and the cerebral cortex. A positive feedback loop increases the output in each sequence of operation of the system. In the cerebro-cerebellar system, these positive feedback loops operate in a fairly simple manner. In the first cerebro-cerebellar sequence, the cerebellum optimizes cortical functions, such as working memory, by making constant adjustments toward optimized problem solving. The cerebral cortex may blend these thoughts (which consist of internal models sent from the cerebellum) with other thoughts to help solve a problem. These new blends are then sent back to the cerebellum where they are further optimized toward additional problem solving. The cerebellum then sends these freshly optimized blends back to the cerebral cortex for even further use and blending toward ongoing problems. This positive feedback loop continues as long as the person repetitively attempts to solve the problem at hand. Each time through the loop, performance is refined and improved.

This book describes, characterizes, and contextualizes how the cerebral-cerebellar positive feedback loop has led to advances in art, science, technology, mathematics, and culture. The chapters of this book describe Einstein's repetitive approach to thinking that led to relativity theory, Mozart's repetitive practice that made him a child prodigy, Maryam Mirzakhani's (and all creative mathematicians) new mathematical discoveries, and repetitive social interaction led to advances in culture. Then, in additional chapters, these ideas are supported by (1) detailed brain-imaging investigations of the cerebro-cerebellar basis of working memory and (2) detailed investigations of cerebro-cerebellar disruptions that can lead to cognitive-affective neuropsychiatric and psychological disorders.

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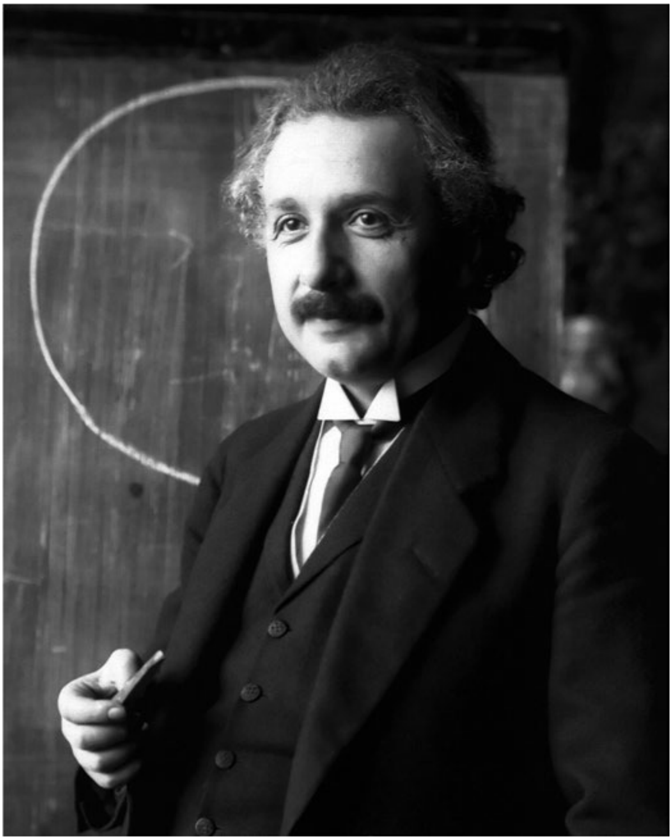
Larry Vandervert, PhD Dr. Vandervert is a retired college professor with published works in the cerebellum's role in creativity, innovation, child prodigy giftedness, and mathematics.

Chapter 1

Psychology and Neuroscience Achieve the Impossible: A New, Revolutionary Look Inside the Cerebellum- Driven Mind of Albert Einstein

Larry Vandervert



Albert Einstein 1921*

Psychology and Neuroscience Achieve the Impossible:
A New, Revolutionary Look Inside the Cerebellum-
Driven Mind of Albert Einstein

Einstein said this about his brilliant ideas:

M. Manto et al., *The New Revolution in Psychology and the Neurosciences*,
https://doi.org/10.1007/978-3-031-06093-9_1

Abstract Can psychology explain the unique brilliance of Einstein's new conceptions of reality? This chapter examines the cerebellum's role in learning internal models (models of everything that is going internal to the cerebral cortex), optimizing them through repetitive thought, and then sending them back to the cerebral cortex for testing. When in the cerebral cortex, these internal models may be blended to bring together visual-spatial working memory and verbal working memory in new ways. This blending that may occur suddenly in the cerebral cortex is used to explain how not only Einstein's sudden intuitions but yours as well.

Einstein Said This About His Brilliant Ideas

> A new idea comes suddenly and in a rather intuitive way. That means it is *not* [italics added] reached by conscious logical conclusions. But thinking it through afterwards you can always discover the reasons which have led you unconsciously to your guess and you will find a logical way to justify it. Intuition is nothing but the outcome of accumulated earlier intellectual experience.[1]

In this chapter you will learn new, revolutionary explanations about how Einstein's intuition actually worked.

Must-Read Quick Overview for All Students

Stunning new lines of brain-imaging research have shown that the brain's cerebral cortex, where traditional psychology has focused its attention, is not alone in producing the basic subject matter of psychology, mind, and behavior! Hundreds of brain researchers from throughout the world have converged to show that the *cerebellum* at the back of the brain contributes previously unknown critical functions to mind and behavior. These newly discovered cognitive functions of the cerebellum include important contributions to skilled movement, language, problem-solving, creativity, and all imaginative thought while they are being used in working memory. *Working memory* is defined as your current thought about what is going on around you. It is what you are using right now to understand what you are reading on this page; it is what you are using when you are attending a class lecture. The important thing is that the new findings about how the cerebellum contributes to working memory permit us to explain for the first time the most highly intriguing yet enigmatic aspects of mind and behavior. *Our new knowledge about the cerebellum truly provides a "new revolution in psychology!"* (Fig. 1.1).

L. Vandervert (✉)
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[1] Albert Einstein's letter to Dr. H. L. Gordon, May 3, 1949. This is Item 58–217 in the Control Index to the Einstein Archive, which may be consulted at Mudd Library, Princeton University.

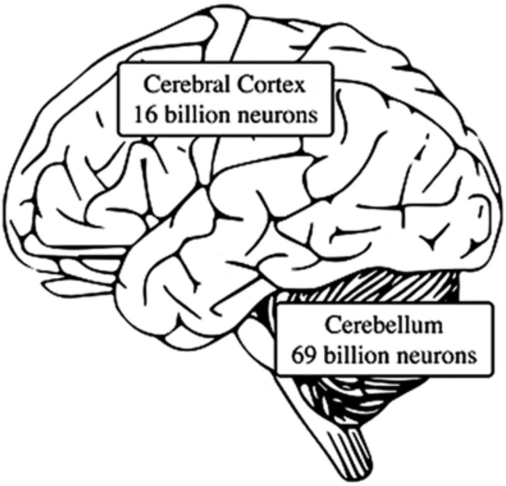

Fig. 1.1 Through evolution, the extension of a massive number of two-way nerve tracks (20 million on each side of the brain) between the *cerebellum* and the frontal and parietal high-level thought and planning areas of the *cerebral cortex*. This latter development means that anything that is repetitively thought about is constantly improved (constantly optimized toward goals) and increasingly automated via more efficient, streamlined modeling by the 69 billion success-predictive neuron circuits in the cerebellum. (Lent et al., 2012)

Working Memory Is the Key to Understanding Einstein's Great Accomplishments

In this initial chapter, a completely new explanation of how working memory processes taking place in the cerebellum and working memory going on in the cerebral cortex teamed up to produce not only everyday working memory but also Albert Einstein's unparalleled powers of deep thought—that is, the new knowledge about the cerebellum allows us to peer into the structure of the entirety of Einstein's working memory! An explanation of Einstein's mind was thought to be impossible, but, now, this chapter is where psychology begins to achieve the impossible! However, this breakthrough about Einstein's mind is only the beginning of the story of the cerebellum. Subsequent chapters in this reader explain the following equally perplexing phenomena: (1) the cerebellum, working memory, and the amazing performances of *child prodigies in music*; (2) the cerebellum, working memory, and how *creativity* happens, (3) the cerebellum and working memory produced *the evolution of language* to become the most powerful general thought processes of human beings; (4) the cerebellum, working memory, and the *origin of mathematics*; (5) the cerebellum and high skills (including signature moves) in all sports; (6) the cerebellum and the origins of human culture and religion; and (7) the cerebellum and movement and mental disorders.

In the context of this huge new direction in brain-imaging research, the student can understand why the picture of Albert Einstein belongs on the cover of this first chapter. The ability to look inside the cognitive structure of perhaps the greatest thinker of our time is one of the newest fronts in an ever-expanding psychology. In this chapter, you'll discover how Einstein was actually freely imagining (just as you often do) when he conceived the development of his special relativity theory and its friend $E=MC^2$!

This first chapter will carefully retrace foundational insights into the *working memory* of the human mind. It then moves swiftly right up to the most recent understandings of how Einstein's own words about his thought process (his own working memory), coupled with brain-imaging studies on the cognitive functions of the cerebellum, can together explain his unparalleled contributions to science. In other words, we will examine how the cerebellum optimized Einstein's thinking that led to his great (perhaps unparalleled) discoveries

**Cover Credit*: This 1921 photo of Albert Einstein is from Wikipedia and is in the public domain. The portrait of Isaac Newton, to be seen later in this chapter, is also in the public domain. All other drawings and sketches were designed and prepared by the author

A New, Revolutionary Look Inside the Cognitive Structure of Einstein's Mind

If you ask people who the most brilliant person was in the last 200 years, without hesitation, most would say that it was Albert Einstein. Many even think he was the most brilliant scientist who has ever lived! In fact, people often refer to any great genius as an "Einstein." Until now, it has seemed impossible to even attempt to explain exactly how Einstein was so brilliant. How did he come up with new theories that entirely changed many of our concepts of physical reality?

In this chapter, psychology achieves the impossible by looking inside the cognitive structure of Einstein's mind. And looking inside the structure of the mind is best done by understanding *working memory*, a key topic in cognitive psychology. As you will learn, working memory is perhaps *the* most key topic in all of psychology—without it you couldn't think!

The Magical Collaboration of the Cognitive Functions of the Brain's Cerebellum and the Cognitive Processes of Working Memory That Take Place in the Cerebral Cortex

To explain how Einstein was able to produce his game-changing theories, we must describe how the cognitive functions of the cerebellum work with the cognitive functions of *working memory*. The *cerebellum* is the part of the brain that ensures that we constantly get better and better at whatever we do *repetitively*, whatever we practice (Ito, 1997, 2005, 2011). Working memory consists of thought that is temporarily kept in mind and solves problems and achieves goals (Baddeley, 2010; Cowan, 2014), and *working memory is repetitively refreshed to keep it absolutely current*. So, anything you're trying to get better at doing in school or that you practice involves a magical symphony of sorts between the cerebellum and working memory! This symphony has been best described by Marvel and Desmond (2010a, b, 2012).

Working Memory

Because people are able to identify directly with the experience of working memory, we will begin this chapter by discussing how it works. Then, we will add the amazing, *silent* contributions of the cerebellum to those processes to begin to get inside the depths of the cognitive structure of Einstein's mind, inside his working memory!

In order to actually get inside Einstein's mind, we will visit three different ways of describing working memory. The *first* description will place working memory in its evolutionary context, so that we can see why it came into being in the first place. A *second* description will provide us with an easy-to-handle conceptual view, so that you can see what working memory is doing, right now, in your own mind, and the *third description* will breakdown the parts of working memory so that we have "stepping-stones" that will begin to move us inside Einstein's brilliant mind.

Working Memory: The Most Significant Achievement of Human Evolution

In the following quote, Patricia Goldman-Rakic, a famous brain scientist, gave us an extremely easy-to-understand yet insightful place to start finding our way into Einstein's mind:

> The combination of moment-to-moment awareness and instant retrieval of archived information constitutes what is called working memory, perhaps the most significant achievement of human mental evolution. It enables humans to plan for the future and to string together thoughts and ideas, which has prompted Marcel Just and Patricia Carpenter of Carnegie-Mellon University to refer to working memory as "the blackboard of the mind." (Goldman-Rakic, 1992, p. 111)

Working Memory Is the Blackboard of the Mind

It has been nearly three decades since Goldman-Rakic (pronounced Ray-keech) penned the above classic statement of working memory. While in those decades the term "blackboard" may have become a little dated, you can just replace it with something like the iPad or iPhone. In fact, the reason iPad-type devices are so popular and useful is that they are, like the blackboard, simply extensions of working memory! If you look over the shoulder of someone using an iPhone, you can watch the flow of part of their working memory! This is the reason that on the cover of this chapter, Einstein is shown standing in front of his ever-present blackboard. *Whatever he put on the blackboard came right out of his working memory!*

Even though nearly 30 years have passed since Goldman-Rakic penned the above quote, most people do not have a clue that *working memory* is “the most significant achievement of human mental evolution.” Furthermore, they have no idea that working memory is, likewise, the most important thing going on in our minds, when you daydream, in the classroom and in the field of psychology itself! *In addition, it will be seen below that working memory is in a very real sense who we are—we even think about ourselves in working memory.*

This little chapter reveals in a simple way what has been recently found about all of this. We will get to the main course, the cognitive structure of Einstein’s mind, in a moment. But, first, let’s get to know working memory a little better.

Working Memory

In the above quote, Goldman-Rakic provided her classic, breakthrough definition of working memory. Nearly all scientists who study working memory would agree with the key parts of Goldman-Rakic’s definition. The *combination* of *moment-to-moment awareness* and instant retrieval of information is what we all experience as ongoing thought or “mind,” and it is the basic stuff of psychology. Working memory is what students (and their teachers) bring to class with them every day, and it is in effect the central part of the student that is *moment-by-moment* watching and listening to everything going on in the classroom, from grade school, through college, and on into marriage and the rest of his or her life. It is, indeed, as Goldman-Rakic pointed out, “the most significant achievement of human mental evolution.” It is *wher*e Einstein was when he discovered that $E = MC^2$! *Working memory is where you are right now as you read this chapter.*

When, for example, we mentally rearrange the furniture in our living room, compare and contrast the attributes of several cars before making a purchase, give directions to your home, or even make change at the grocery store, we are experiencing working memory. Another extremely important, but not often cited, example of working memory occurs whenever a person thinks about and responds to items in a psychological test of, for example, personality, intelligence, or, of course, creativity. Working memory is also at “work” in the high-level performances of experts in all fields (chess, music, sports, in child prodigies, on-the-feet thinking of seasoned professors, and so on [Ericsson et al., 2007]). Ah, child prodigies were mentioned. With child prodigies, we are moving closer to getting inside the cognitive structure of Einstein’s mind! More on child prodigies will be discussed in the next chapter.

The Evolution of Working Memory and the Explosive Enlargement of the Cognitive Functions of the Cerebellum

How did humans obtain such an interesting and powerful working memory? Approximately 1.7 million years ago, human working memory began to evolve toward its present form through the natural selection of the highly repetitive cognitive requirements of making stone tools (Stout & Chaminade, 2009, 2012; Stout & Hecht, 2017; Vandervert, 2018, 2020a).

Neuroanthropologists (anthropologists who study the evolution of the brain) Stout and Hecht (2017) referred to such stone-tool making as imitative or "high-fidelity" social learning. As an example of this social learning, they describe how it takes place (and took place about 1.7 million years ago) between a learner and a teacher:

> 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. 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. 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. 7862–63)

Ancient peoples (e.g., *Homo erectus*) had to use their early thought processes such as silent vocalizations to follow strict sequences of knapping. As described above, knapping involves striking stones with other stones to shape them toward becoming sharp tools—this requires mentally following an imagined sharp tool outcomes in working memory. Therefore, the precision knapping requirements of making stone tools favored the natural selection of rule-governed processes in working memory and drastic, orderly structuring of working memory eventually led to the selection of language (Vandervert, 2011, 2016a, 2018, 2020a, b). Moreover, a careful reading of the above quote reveals all the moments of the natural selection of a cerebra-cerebellar system learning and evolving toward the control and prediction of the kinematics (movements) and dynamics (forces) of what we now call physics (Vandervert & Moe, 2021; Van Overwalle et al., 2019).

The cerebellum did all of this through the selective advantage of detecting and recording the *sequences* of steps in all movements and thought (Akshoomoff et al., 1997; Leggio & Molinari, 2015), and the cerebellum refines (optimizes) this pattern of recorded sequences each time the movements or thoughts are repeated—until it gets the sequence related to a desired goal perfect! Armed with these recorded sequences, the cerebellum can send patterns (models) of constantly optimized sequences to the cerebral cortex via the cerebellum's anticipatory forward control movement and thought (Van Overwalle et al., 2019) in working memory. Often, newly optimized patterns from the cerebellum are suddenly blended in the cerebral cortexes movement and working memory areas and the person experiences an "out-of-the-blue" idea or perhaps a new signature move in sports (Imamizu et al. 2007; Vandervert et al. 2007).

During this evolutionary 1.7 million years or so, the cerebellum enlarged three- to fourfold in size and acquired huge new areas devoted to thought process, including language (Leiner et al., 1986, 1989; Marvel & Desmond, 2010a, b, 2011, 2012). Recall that Patricia Goldman-Rakic above-described working memory as *moment-to-moment* awareness of thought. These means that working memory is naturally *very highly repetitive* in keeping your thoughts up-to-the-minute, actually keeping them up-to-the-second (Baddeley, 2010; Vandervert, 2009a, b). Through these rapid repetitions of thought (you are unaware of these repetitions), the cerebellum has the specific job of making your working memory (1) faster, (2) more appropriate to the job at hand, (3) more unconsciously automatic, and (4) more predictive in ways that solve current problems you are facing (Ito, 1997, 2005, 2011). As Goldman-Rakic would point out, these are all evolutionary advantages that occurred through natural selection.

Some Details of Working Memory Before Going Inside Einstein's Mind

Let's nail down more of the classically accepted details about working memory. Working memory has also been called the conscious, cognitive "hub" (Haberlandt, 1997, p. 212) for all learning and experience that involves thinking. For this everyday experience of working memory, Cowan (1999, 2014) provided the following widely accepted, straightforward definition:

> Working memory refers to cognitive processes that retain information in an unusually accessible state, suitable for carrying out *any task with a mental component* [italics added]. The task may be language comprehension or production, problem-solving, decision-making, or other thought. (1999, p. 62)

Working memory provides what you are taking-in or know about in "any task with a mental component"; it therefore comprises your moment-to-moment awareness during learning, thinking, and *problem-solving* in music, art, business, industry, all academic subjects, and sports. In passing, it can be seen from Cowan's above quote that working memory is worlds more intricate and "mindful" than the more simple idea of *short-term memory*—the two are often confused (see http://en.wikipedia.org/wiki/Short-term_memory).

Why Working Memory May Be the Most Important Idea in Psychology

As you are beginning to appreciate, everything that you will learn about psychology and everything you will ever think about psychology will be processed through your working memory. As you read this chapter about various principles of psychology, *your working memory will even formulate your understandings of working memory itself!* I will state the overriding point of this chapter straight out: *Working memory can be seen as the most important idea in psychology—working memory must be there—both your professor's working memory and yours!* Without working memory, you would know pretty much nothing. And, on the flipside, it's really the only framework that can allow us to get inside Einstein's mind. Substantial proof of these statements comes from an accident where a man temporarily completely lost his working memory. See Box.

Box: What You Would Be Like Without Working Memory?

Psychologists often find out how important psychological processes work and what role they play in everyday behavior when they come across someone who suddenly appears to be missing those processes.

Here is an excerpt from case study of a man who appeared to have completely lost all of the moment-to-moment awareness and instant retrieval of information from his long-term memory. In other words, his working memory had shut down operations.

> The Rev. Mark Hanna found that, after a minor carriage accident, he had totally lost his memory of his entire past life. As described by Sidis and Goodhart, he appeared on initial examination to be like a helpless infant. He knew no one, not even close family members; had no idea where he was; was unaware of the significance of common, familiar objects; and was completely without language. His mind was, in other words, a veritable *tabula rasa*. (Kaplan & Sadock, 1983, p. 948)

Without working memory your mind, too, would be a tabula rasa (a blank slate). Is this *really* what you'd be like without working memory? Yes, it is. And you can see why working memory has to be the most important concept in psychology. Can you see why, without working memory, there was hardly any "psychological" substance to Rev. Mark Hanna, and there could also

(continued)

Box (continued)

hardly be *any* psychology? Working memory is the only uniquely human experience of "mind" we ever have. At the time of the Hanna case, the concept of working memory did not yet exist. See the original, larger Internet source for the account of the Hanna case (1904) at bottom inside of this Box.

It is important to note that the Reverend Mark Hanna still had his complete, archived long-term memory—there simply was no working memory to access his long-term memory. Hanna's working memory later suddenly popped-up as if out of nowhere, and he seemed normal again—his working memory had returned. He simply had temporarily lost control of his moment-to-moment awareness and instant retrieval of long-term memory information—he had temporarily lost his working memory.

For detailed accounts of the Hanna case, go to this web page: http://www.sidis.net/mpcontents.htm

The Components of Working Memory That You Actually Experience: An Operational Definition

So, what is it going to be like when we go inside Einstein's mind? Can we picture it on the "blackboard of the mind" mentioned earlier? Alan Baddeley (1992, 2010), a leading working memory researcher and theorist, provided what we will call "stepping stones" that will take us right inside Einstein's mind (his working memory).

Baddeley described three stepping stones leading into the working memory experience: (1) You have a visual imagination. (This is the "blackboard" part of the mind; Baddeley called it a *visual-spatial sketch pad)* 2. You talk to yourself either silently or out loud and often imaginatively (Baddeley called this *a speech loop)*. and 3. You can focus your *attention* on different parts of the blackboard or different parts of what you are saying to yourself. This focusing of attention is the work of your *central executive* of working memory. These are the building blocks of thought you'll find in your own moment-to-moment awareness. It must be pointed out that Baddeley's approach to working memory is the most *operationally* defined of the approaches to working memory. That means that that each part of Baddeley's approach suggests a set of laboratory procedures or operations that can be used to scientifically measure working memory as it takes place. See Vandervert (1996) for an easy-to-understand explanation of operational definitions in science.

Here's an example of how you experience these components of working memory, although constantly being mixed, blended, and updated in interesting ways:

1. You see images in the visual-spatial "sketch pad" (pictures, pieces of pictures, fleeting sketches—we'll see how Einstein described it in a moment) in the imagination of your thoughts.
2. You talk to yourself, listen to others talk, read about things, listen to music, or view art, all of which constantly bring images and meanings out of your long-term memory.

3. You constantly focus and shift your attention to make decisions about what other images to retrieve from your more permanent, long-term memory, what to keep or discard, and what to blend into your ongoing imagination.

This is a closer look at the working memory you and your teachers and professors bring to class; working memory *is* academic learning, creating, and thinking—it *is*, by definition, the mental life of which we are *aware*, not only when we are awake but even when we dream! Learning about working memory even improves your working memory! The above components of working memory are some of the things we will find upon entering Einstein's mind.

But, First, There Is One More Important Thing You *Must* Understand About Working Memory: How *Concepts* Originate

Through the entire processes of both the evolution of working memory and of everyday thinking in working memory, *working memory constantly produces new concepts*. In this regard, Nelson Cowan, perhaps the most widely read expert on working memory in the United States, has called working memory the cauldron of new *concept* formation (Cowan, 2014, p. 210). This means that when you learned, for example, what a zebra was, your working memory simply blends your existing concept of a horse with the concept of strips. Suddenly your working memory knows what a zebra is like, in other words, your working memory has formed a new concept, the concept of a zebra.

This process in working memory begins in the cerebellum where the individual concepts of a horse and of strips were originally optimized through repeated exposure to them and are constantly refined through additional repetition and then sent to the cerebral cortex, where they are blended into concepts when needed (Vandervert, 2003a, b, 2007, 2015; Vandervert et al., 2007). This process occurs as a *positive feedback loop*. A positive feedback loop may be understood as follows: When output of the system is feedback, it increases the magnitude of the quality and/or quantity of the loop's next output and so on.

A Positive Feedback Loop Between the Cerebellum and the Cerebral Cortex Constantly Enhances the Contents of Working Memory

Each time cerebellar internal model blends are executed in working memory in the cerebral cortex, these blends are then sent back to the cerebellum for a new round of optimization. These new optimizations are then sent to working memory in the cerebral cortex for the execution of new improved (and perhaps unique) experience.

This positive feedback loop optimizes and blends ad infinitum as long as the person thinks about a particular problem.

Let's Look Inside Albert Einstein's Working Memory and His Concepts

Now, we are ready to take a look inside the cognitive structure of Albert Einstein's mind. Einstein gave us a great picture of what his working memory was like when it was actually going on in his mind. Here is what he described as "thinking":

> What, precisely, is "thinking"? [Of course, we now call "thinking" working memory.] When, at the reception of sense-impressions, memory-pictures emerge, this is not yet "thinking." And when such pictures form series, each member of which calls forth another, this too is not yet "thinking." When, however, a *certain picture* [italics added—recall that there are visual-spatial picture in working memory] turns up in many such series, then—precisely through such return—it becomes an ordering element for such series, in that it connects series which in themselves are unconnected. Such an element becomes an instrument, a concept. I think that the transition from free association or "dreaming" to thinking is characterized by the more or less dominating role which the "concept" plays in it. It is by no means necessary that a concept must be connected with a sensorily cognizable and reproducible sign (word); but when this is the case thinking becomes by means of that fact communicable. (Einstein, *Autobiographical Notes*, 1949, p. 7)

This whole thing might sound a little complicated, but keep your attention (your central executive) on Einstein's "memory-pictures." In this description of "thinking," Einstein said that memory-pictures drive the flow of thoughts in his working memory. This flow of memory-pictures is a perfect example of how series of visual-spatial pictures are mentally drawn on "the blackboard" (iPad) of the mind," much as Goldman-Rakic suggested. Figure 1.2 (below) is a simplified sketch of this flowing cognitive structure to help visualize Einstein's words *in your own working memory*. For more examples of the different kinds of images Einstein "saw" in his thinking, see Vandervert et al. (2007, pp. 12–15).

Notice that Einstein says a "certain picture" turns up and represents the formulation of a concept. Often, this certain picture represents a totally new concept. And it is important to recognize that, in Einstein and in everyone else, all new ideas are the product of processes going on in this "cognitive structuring" of working memory. Recall that Cowan (2014) argued that working memory is the cauldron of concept formation. We will turn to a discussion of how this certain picture comes about below.

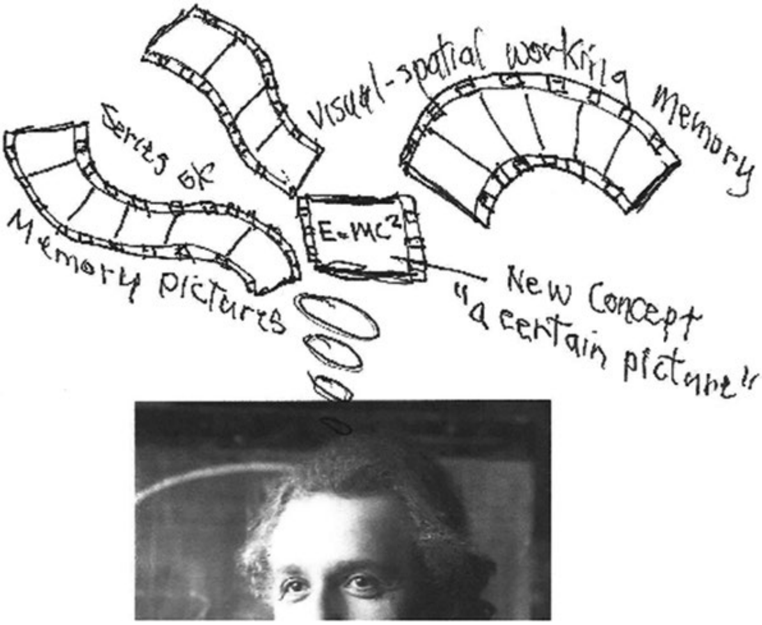

Fig. 1.2 Einstein's two "working blackboards": one on the wall behind him and one in his head

Capturing Einstein's Working Memory in the Classroom

Einstein's description of working memory reveals a very important lesson about how thought comes about in working memory: Thought begins with visual-spatial series of pictures which then form concepts, recall that working memory is the cauldron of concept formation. This idea of Einstein's has been strongly supported by a recent, new explanation about how not only thought, but language itself came about in evolution and comes about in the development of every child. Vandervert (2009a, b, 2011, 2016a, b) proposed that visual-spatial thought came first during the evolution of humans and that early human vocalizations were *sequenced* and *blended* with the memory-pictures so that sound patterns (forming early "words") could be used as tags or labels for concepts in working memory, and thus language was born (Vandervert, 2020a, b).

Einstein's "Memory-Pictures" Begin as the First Cognitive Structures in Every Infant

Extensive studies have found that the foundational structure of working memory begins in every infant with *visual-spatial concepts* (Mandler, 2004). These first "conceptual memory-pictures" are the foundation upon which language will obtain its meaning (Mandler, 2004; Vandervert, 2009a, b, 2011, 2013b, 2015, 2016b, c).

Interestingly (very interestingly), these first infant concepts formed a primitive physics for the infant—these concepts helped the infant begin to understand how the world around it works (Vandervert, 2015, 2016a). In other words, this first structure of visual-spatial memory-pictures provides the meaningful working memory about the real world that can reveal what leads to what and with enough repeated thinking over time so that it involves the cerebellum eventually formulate fundamental things (concepts) like $E = MC^2$.

This foundational structuring of cognition in series of memory-pictures means that all learning can be strongly promoted by, for example, having children develop storyboarding for everything they learn. A storyboard is a series of sketches that illustrates how a story or process will unfold, or how to best have it unfold. (See http://www.scholastic.com/teachers/article/what-are-storyboards) Story-boarding encourages the necessary, thought-rich and contextual visual-spatial experience that Einstein described. In teaching any topic storyboards can be used so that both the teacher and the students can see the "thinking" of everyone involved—everyone can see those "certain pictures" as they arise, and it reveals what the cerebellum has learned through the repetition that led to the story boards in the first place!

Achieving the Impossible: Do We Know How Einstein's "Certain Picture" (A Concept) Arises?

How does that "certain picture" arise in Einstein's mind and then connect the series of memory-pictures "which in themselves are unconnected." It has recently been found that the mental experience of working memory is actually far *more* than even the rather magical moment-to-moment awareness and instant retrieval of information. But how could working memory be more than our ongoing experience? Sound impossible? With the cerebellum on the job, it's actually quite simple.

The Cerebellum: Its Game-Changing Role in Guiding Thought Toward Einstein's "Certain Picture"

Athletic coaches and trainers know that no matter how much natural physical prowess an athlete has been genetically given, one thing is important above all else—practice, practice, practice. And most, if not all, educators are aware of the powerful effects of *deliberate practice* which Anders Ericsson and his colleagues found across many fields of study (e.g., Ericsson et al., 1993, 2007). *Deliberate* practice is defined as extended practice where the child, athlete, scientist, artist, or musician works many additional hours (usually alone) on specific parts of their skills they have not yet completely mastered. Deliberate practice applies to child prodigies (Vandervert, 2016a, b) and even Einstein's life story in science (Einstein, 1949; Vandervert, 2015). But just how do mere repetitive practice and even the strategy of *deliberate practice* get the brain to manufacture improvements and highly creative athletic, scientific, and artistic performance? How does it get the brain to achieve the impossible?

Neuroscientists have long had a pretty good idea that the quiet, unconscious improvement of physical and mental skills, including, in some cases, super, almost otherworldly performance (like Einstein's, Edison's, or Newton's), is facilitated greatly by functions of the little cerebellum at the back of the brain (Leiner et al., 1986, 1989; Vandervert, 2015; Vandervert et al., 2007). The cerebellum can be seen at the back of the brain seen earlier in Fig. 1.1. The rest of the brain in the illustration is the cerebral cortex. Again, the cerebellum may be small, but it sends 40 million two-way nerve tracts throughout the brain, whereas there are only 2 million nerve tracts connecting the eyes to the visual areas of the brain. Cerebellum researchers Bostan et al. (2013) have concluded that the cerebellum is as involved in the control and improvement of thought as it is in the control and movement of the movement of the body. In addition, the little cerebellum contains a whopping 80% of the brain's total number of neurons, whereas the huge cerebral cortex contains the rest, only 20%—the cerebellum's neurons are very small and very compact (Lent et al., 2012).

Recently, neuroscientists expanded their views about the ability of the cerebellum to "silently" cover not only all physical movements but also all thoughts. The cerebellum plays a much bigger role in super streamlined performance of both movements and working memory than anyone once imagined.

The cerebellum seems to be a *silent* little genius (we are never aware of it doing its work) at designing neural "software" for working memory. It silently facilitates thinking about everything from Einstein's world-shaking concepts to everyday creativity and child prodigies! Award-winning cerebellum researcher Masao Ito (1997, 2005, 2008, 2011; Vandervert, 2015) found that the cerebellum does this by reorganizing and streamlining physical movements and thoughts to make them faster, more efficient, and more appropriate. This is the first, clearly identifiable part of the story that led to Einstein's certain picture! Things that are thought about are constantly being streamlined, whether you are aware of it or not! Gilchrist and Cowan (2010) pointed out that much of working memory goes on at an *unconscious* level, and the cerebellum is how it does it (Vandervert, 2015). In his 1949 *Autobiographical Notes* (cited above), Einstein, too, said that "thinking" goes on at an unconscious level: "For me it is not dubious that our thinking goes on for the most part without use of signs (words) and beyond that to a considerable degree unconsciously" (p. 9).

How the Cerebellum Silently Contributes to the Sequencing and Blending of Memory-Pictures: The Silent Blending of Ideas Toward Creativity and Intuition

In addition to Masao Ito's findings on streamlining, Imamizu and Kawato (2012) and Imamizu et al. (2007) discovered processes that *blend* thoughts in working memory. Their findings describe how, when people are trying to solve new problems, thoughts are received in the cerebellum from the cerebral cortex, *are reformulated into streamlined, hybrid series* while in the cerebellum and then sent back again to the cerebral cortex where new, imaginative blends occur. Yomogida et al. (2004) had earlier found that, indeed, the cerebellum and cerebral cortex collaborate in blending visual images during problem-solving. But at that time, the full implications of Yomogida et al.'s findings were not realized.

All of these brain-imaging studies strongly suggest that this blending process is, indeed, how the "certain picture" Einstein described comes into being. Vandervert (2009a, b, 2016a, b) has described how this same blending process, although accelerated, explains the amazing performance skills of child prodigies. In passing, it is important to point out that this blending-based explanation of Einstein's genius fits well the findings of recent brain-imaging studies conducted on Einstein's actual, long-preserved brain that revealed extra-rich connections between its two cerebral hemispheres (Men et al., 2013).

The Impossible Achieved

We can refer to these new, better creations of the cerebellum and cerebral cortex as *creativity* and *intuition*. They are the "certain pictures" or concepts which Einstein described, and Einstein himself thought that all concepts were the result of creative intuition (Einstein, 1949):

> A new idea [a new concept in working memory] comes suddenly and in a rather intuitive way. That means it is *not* [italics added] reached by conscious logical conclusions. But thinking it through afterwards you can always discover the reasons which have led you unconsciously to your guess and you will find a logical way to justify it. Intuition is nothing but the outcome of accumulated earlier intellectual experience.[2]

When these new blends of the "certain memory-pictures" in Fig. 1.2 are recognized in working memory, a new idea pops into our heads from seemingly nowhere. This is the "a ha" moment, this is intuition, and Vandervert (2009a, 2011, 2015) argues that this is the basis of all creativity.

Isaac Newton Was an "Einstein": Apples Falling Sideways?

All thinking, great and small, comes about through the kind of blending of memory-pictures that Imamizu and Kawato's (2009, 2012) research discovered and that Einstein described. Einstein, himself, even commented that all thinking took place *in the same way* that he described in his quote about memory-pictures.

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[2] Albert Einstein letter to Dr. H. L. Gordon, May 3, 1949. This is Item 58–217 in the Control Index to the Einstein Archive which may be consulted at Mudd Library, Princeton University.

Isaac Newton public domain painting

A classic, widely known example of discovery by blending of new, hybrid series of memory-pictures occurred when a falling apple gave Isaac Newton's the then "new" idea of "gravitation." Newton recounted the moment to his good friend, William Stukeley:

> After dinner, the weather being warm, we went into the garden and drank thea [tea], under the shade of some apple trees...he told me, he was just in the same situation, as when formerly, **the notion of gravitation** [bold added] came into his mind ["gravitation" was a new concept]. It was occasion'd by the fall of an apple, as he sat in contemplative mood. Why should that apple always descend perpendicularly to the ground and not sideways or upward? thought he to himself.... (Biographer and friend, William Stukeley, *Memoirs of Sir Isaac Newton's Life*, 1752)

In Newton's mind, as in Einstein's, this thinking consisted of a series of memory-pictures. Only in Newton's case, the various possible motions of the apple were blended into a certain picture; it led to his new concept of gravitation. Newton's *certain picture* was the idea or concept of "gravitation," that is, something pulled on things in a certain direction—downward! As in Einstein' case, Newton's continued, repetitive imaginative thoughts about moving celestial bodies kept optimizing his working memory toward the mathematical form of the law of gravitation.

This all may sound silly or like "of course apples don't fall sideways." But people before Newton just took the fact that things fell "down" for granted, and not that something called gravity was doing it! Taking into account William Stukeley's memoir along with what Newton decided about gravity, can we imagine some of the "sideways" or "upward" memory-pictures that Newton probably saw in his working memory?

Conclusions

Working Memory, the Cerebellum, and Creativity

It seems Imamizu and Kawato's (2009) discovery of how mental skills are blended toward new concepts is as important to the neurosciences as Einstein's E=MC2 was to physics! Vandervert et al. (2007) and Vandervert and Vandervert-Weathers (2013) proposed that the combined processes of the cerebellum and the cerebral cortex build new, super performance skills of not only movement and "thought" in general but also every detail of what goes on in the thought processes of working memory; it appears to be the way all creative ideas come about. Vandervert (2017) has proposed how the cerebellum is even responsible for the origin of mathematics. And Einstein believed that mathematics was the basis of his creativity (1954, p. 274).

Within the view of this chapter, the thought-related super skills manufactured in the cerebellum are the main players in the formation of creative ideas, including everything from Einstein's theories of relativity to Newton's idea of gravitation to, for example, Picasso's cubism or a signature basketball shot by Michael Jordan. These researchers argue that an idea might start in the brain's cerebral cortex, but it gets its "creative punch" from the streamlining silently at work in the cerebellum. And, as Ito (2005) says, this goes on silently (unconsciously), and eventually with hard work new ideas just pop into our heads—that is, when that *certain picture* pops up.

As a student, the most important thing for you to "take home" from this chapter is that you have basically the same working memory as Einstein (or Newton), and it works in precisely the same way as Einstein's. Along this line, Einstein said that science is simply the refinement of everyday thinking:

> The whole of science is nothing more than a refinement of everyday thinking. It is for this reason that the critical thinking of the physicist cannot possibly be restricted to the examination of the concepts of his own specific field. He cannot proceed without considering critically a much more difficult problem, the problem of analyzing the nature of everyday thinking [working memory]. (Einstein, 1954, p. 290)

Directly in regard to the lesson of this quote, Einstein (1949, p. 53) told of his thoughts at age 16 where he wondered what it would be like to travel along side of a beam of light at 186,000 miles a second. He pondered and *played* with that thought for 10 years (most importantly in his cerebellum) and directly from it eventually came up with his theory of special relativity (Vandervert, 2015). Through repetition in working memory, creativity is the product of new ideas that are blended below the level of consciousness and come to consciousness in the conceptual process going on in working memory.

Psychology Achieves the Impossible: A Story of Creativity (Essay Questions)

Here are Five Essay Exercises That Will Get Memory-Pictures Flowing in Your Working Memory In this chapter, working memory is presented in a fresh, new way. While remaining completely true to the accepted concepts of working memory, the following five essay exercises for this chapter explore the leading-edge science behind how, as Goldman-Rakic's quote at the beginning of this chapter suggests, working memory became "the most significant achievement of human evolution." Suggestion: Reread this quote before continuing.

1. What was it like inside the cognitive structure of Einstein's mind? Was Einstein's mind really different from your own working memory? If there are, there differences indicate how Einstein's was different.
2. Could we define psychology as the scientific study of development, operation, and products of human working memory? Why, why not?
3. Since the cerebellum records sequences that enable automaticity in arithmetic calculations (Vandervert & Moe, 2021), would it be possible to design a computer that worked in the same way as the cerebellum? Hint: See Leiner and Leiner (1997).
4. Did, in principle, Einstein's and Newton's minds work in the same way as everyone's mind, or did they have something "extra" going for them?
5. Cowan provided a *conceptual* definition of working memory, and Baddeley provided a set of *actual operations* in working memory. Indicate which type of definition you like better and why you prefer it.
6. Describe what is meant by a *positive feedback loop* between the cerebellum and the cerebral cortex.

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

Larry Vandervert

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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M. Manto et al., *The New Revolution in Psychology and the Neurosciences*,
https://doi.org/10.1007/978-3-031-06093-9_2

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.

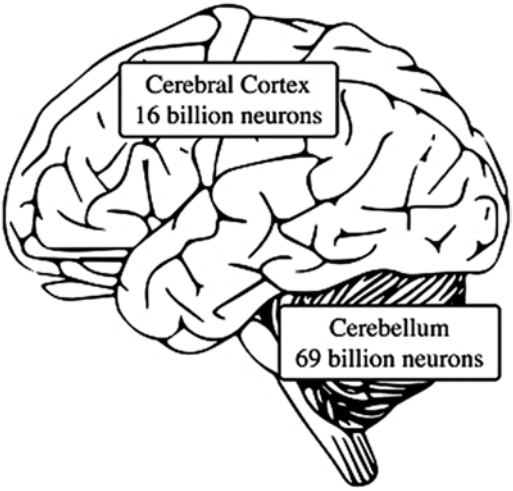

Fig. 2.2 Any repetitive movement or thought that is constantly improved (constantly optimized toward goals) and increasingly automated via more efficient, streamlined internal models by the 69 billion success-predictive neurons in the cerebellum (Lent et al., 2012). Cerebellar internal models consisting 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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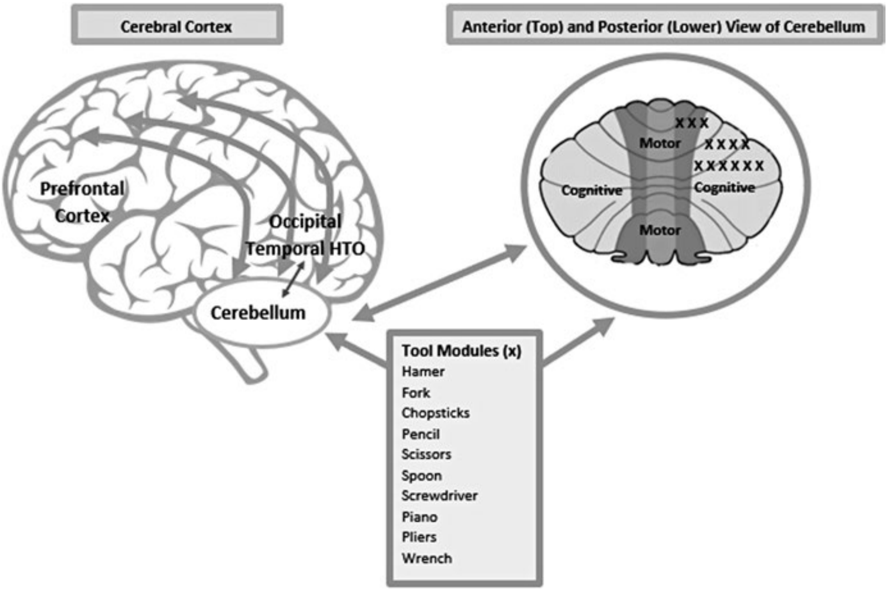
[1] In the stone-tool making view of the evolution of the autobiographical knowledge/self, it is important to point out that autobiographical knowledge/self includes components which span the order of increasing adaptive optimization across the evolution of *Homo sapiens*, namely, spatial-visual, semantic 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



Tool Modules (x)
Hamer
Fork
Chopsticks
Pencil
Scissors
Spoon
Screwdriver
Piano
Pliers
Wrench

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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Chapter 3
The Social Origin of Mathematics and Number Sense in the Cerebellum

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Photo courtesy *Jan* Vondrák

Stanford mathematics professor Maryam Mirzakhani was the first and to-date only female winner of the Fields Medal since its inception in 1936.

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https://doi.org/10.1007/978-3-031-06093-9_3

Abstract Mathematicians and scientists have struggled to adequately describe the *ultimate foundations* of mathematics. Nobel laureates Albert Einstein and Eugene Wigner were perplexed by this issue, with Wigner concluding that the workability of mathematics in the real world is a mystery we cannot explain. In response to this classic enigma, the major purpose of this chapter is to provide a discussion of the ultimate origin of mathematics and "number sense." It is proposed that the origin of mathematics occurred through the collaboration of the cerebellum and the cerebral cortex (but prominently cerebellum driven). This model is based upon (1) the modern definition of mathematics as the "science of patterns," (2) cerebellar predictive sequence (pattern) detection, and (3) findings that the manipulation of numbers is automated in the cerebellum. It is argued that during infancy, the cerebellum learns (1) a first tier of internal models for a primitive physics that constitutes the foundations of visual-spatial working memory and (2) a second (and more abstract) tier of internal models based on the phonological loop of working memory that brings the kinematics and dynamics of the first-tier consciousness in verbal working memory. It is concluded that difficulty with "number sense" results from the extended demands on executive control in learning inverse dynamics models associated with cerebellar inner speech related to the second tier of abstraction (phonological consciousness and numbers) of the infant's primitive physics.

Tough Problems Are the Most Fun!

The quadrennial Fields Medal, which Mirzakhani *won in 2014*, is the most prestigious award in mathematics, often equated in stature with the Nobel Prize. Mirzakhani specialized in theoretical mathematics that read like a foreign language by those outside of mathematics: moduli spaces, Teichmüller theory, hyperbolic geometry, ergodic theory, and symplectic geometry.

Mastering these approaches allowed Mirzakhani to pursue her fascination for describing the geometric and dynamic complexities of curved surfaces—spheres, doughnut shapes, and even amoebas—in as great detail as possible. Her work was highly theoretical in nature, but it could have impacts concerning the theoretical physics of how the universe came to exist and, because it could inform quantum field theory, secondary applications to engineering and material science. Within mathematics, it has implications for the study of prime numbers and cryptography.

A self-professed "slow" mathematician, Mirzakhani's colleagues describe her as ambitious, resolute, and fearless in the face of problems others would not, or could not, tackle. She denied herself the easy path, choosing instead to tackle thornier issues. Her preferred method of working on a problem was to doodle on large sheets of white paper, scribbling formulas on the periphery of her drawings. Her young daughter described her mother at work as "painting."

"You have to spend some energy and effort to see the beauty of math," she told one reporter.

In another interview, she said of her process: "I don't have any particular recipe [for developing new proofs]. … It is like being lost in a jungle and trying to use all the knowledge that you can gather to come up with some new tricks, and with some luck you might find a way out."

This information is courtesy of the Stanford News Library.

Also, it is recommended that the students see the video "Secrets of the Surface" produced in 2022 by Zala Films (http://www.zalafilms.com/secrets/). In this video, it can how as quoted, "You have to spend some energy and effort to see the beauty of math." It takes practice, practice, practice, and trial and error. In a word, it takes the cerebellum!

Must-Read Quick Overview for All Students

In this chapter, you will learn that mathematics is defined as the "*science* of *patterns*." Notice that both terms in this definition have been highlighted to show they are equally important. In this regard, you are asked to pay careful attention that the kinematics (movements) and dynamics (forces) of phenomena that these patterns describe were naturally selected into the cerebro-cerebellar system of humans during approximately 1.7 million years of the evolution of stone-tool making. Stone-tool making is all about learning the precise, predictive forward control of the kinematics and dynamics associated with the shaping of stone tools. Keep in mind that the cerebellum learns patterns of action and thought toward this predictive control—thus, its learning of internal models (models of what is going on internally in the cerebral cortex) can account for both the science and the patterns that, together, constitute mathematics. In this chapter, you will discover how a science of these patterns comes to be manipulated in the consciousness of both visual-spatial and verbal working memory. In this regard, it is important for you to go back and carefully reread Professor Maryam Mirzakhani's story—we will return to her hard work and fascination with the visual-spatial world.

The Social Origin of Mathematics and Number Sense in the Cerebellum

Introduction

Scientists and mathematicians have long been baffled, yet deeply intrigued, by the workability of mathematics in the "real world." For example, Einstein (1954) asked, "How can it be that mathematics, being after all the product of human thought which is independent of experience, is so admirably appropriate to the objects of reality?" This same question, though stated quite differently, is implicit in this title of a classic chapter by another Noble laureate, Eugene Wigner (1960), "The Unreasonable Effectiveness of Mathematics in the Natural Sciences." Wigner concluded his chapter with this statement of puzzlement:

> The miracle of the appropriateness of the language of mathematics for the formulation of the laws of physics is a wonderful gift which we neither understand nor deserve. We should be grateful for it and hope that it will remain valid in future research and that it will extend, for better or for worse, to our pleasure even though perhaps also to our bafflement, to wide branches of learning. (p. 14)

To help shed light on this "miracle" of the language of mathematics, leading computer scientist and mathematician Derek Abbott (2013) proposed that the origin of mathematics is not a mystery but rather is a product of the human mind. In this regard, Abbott argued strongly against what he calls "mathematical Platonism," the idea that mathematics has a mysterious, independent existence from the human mind. However, in his alternative explanation, he was only able to conclude that "mathematics is a product of the imagination that sometimes works on simplified models of reality" (p. 2152). He did not specify how in imagination these simplified models of mathematics might originate or how we might come to know of them.

What Is Mathematics?

With the development of computers and new applications such as those of Maryam Mirzakhani (pictured at the beginning of this chapter), mathematics has developed beyond its historical definitions of number and geometry. Lynn Arthur Steen (1988) (at the time Chairman of the Conference Board of the Mathematical Sciences) defined mathematics "the science of patterns":

> Mathematics is the science of patterns. The mathematician seeks patterns in number, in space, in science, in computers, and in imagination. Mathematical theories explain the relations among patterns; functions and maps, operators and morphisms bind one type of pattern to another to yield lasting mathematical structures. Applications of mathematics use these patterns to "explain" and predict natural phenomena that fit the patterns. (p. 616)

See also Devlin's (1994) complementary description of mathematics as the science of patterns which includes the study of the patterns of shape, motion, number, and behavior.

Purpose

The purpose of this chapter is to describe how newer understandings of the prominent role of the human cerebellum in the cerebro-cerebellar development of science (Vandervert, [4]) in culture (Vandervert, 2016) and in social cognition (Van Overwalle et al., 2019) can be extended to (1) provide a way to address the longstanding "mystery" of the workability of mathematics in the real world and (2) provide a basis for how thought (or imagination) can produce mathematics through the manipulation of Abbott's (3) suggestion of simplified models of reality. In overview, these newer understandings are based on the works of Baddeley et al. (1998);

Ito (1993, 1997, 2008, 2011); Leiner et al. (1986, 1989); and Van Overwalle et al. (2019). Vandervert (2019, 2020a) and Vandervert and Moe (2021) proposed that the foundations of our scientific knowledge of patterns that constitutes mathematics evolved in the human brain during approximately 1.7 million years of rigorous, repetitive social interaction required in stone-tool making. Within this theoretical perspective, Vandervert argued that the patterns that constitute mathematics (1) evolved in cerebellar internal models of repetitive *patterns of predictive sequences* (Leggio & Molinari, 2015) of detailed cause-and-effect-related kinematics and dynamics of socially modeled patterns of stone-tool making actions and cognition (Vandervert, 2018) and (2) evolved as the basis for mentalized forms of knowledge within Theory of Mind (ToM) through the phonological loop of inner speech (Vandervert, 2020b, c) representing the socially modeled kinematics and dynamics of other bodies in (1). That is, the capacity for a knowledge of the patterns of mathematics evolved in inner speech as manipulated within ToM (one's simulative capacity of making automatic and intuitive anticipatory inferences about the mental states of others) (Vandervert, 2020b, c; Van Overwalle & Mariën, 2015; Van Overwalle et al., 2019). Put simply, this overview of cerebro-cerebellar research strongly suggests that mathematics originated in kinematic and dynamic patterns in social cognition, is manipulated in inner speech of the phonological loop of working memory, and, thereby, comes to consciousness. It is important to note in regard to the second portion of the above argument (2) that following Baddeley et al. (1998), the phonological loop evolved in working memory primarily to learn new word forms—more will be said of the evolution of the phonological loop in subsequent sections of this chapter.

Within the forgoing cerebro-cerebellar framework, the following forward control of sequences of social cognition (Van Overwalle et al., 2019) are argued to provide the above predictive social basis of patterns that constitute mathematics:

> 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* [italics added], and to instantly detect disruptions in action sequences. These are important social functions. Consequently, if neurological disorders affect the cerebellum, detrimental effects on social functionality might be found, especially on more complex and abstract social cognitive processes. 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. (p. 35).

Autobiographical knowledge here refers to one's fluent or automatic knowledge (including abstract knowledge) of past and future action/interaction sequences related to the self. See Martinelli et al. (2013) for a discussion of the components of autobiographical knowledge.

In this chapter, we will describe the specific socially driven brain mechanisms underlying mathematics that allow this "science of patterns," as Steen's above definition described, "to 'explain' and predict natural phenomena that fit the patterns."

In recent decades, abundant imaging research has found that the cerebellum is a master computational system for both motor and cognitive areas of the cerebral cortex (Akshoomoff et al., 1997; Leggio & Molinari, 2015). Within the context of these findings and within the context of mathematics as the science of patterns, it is proposed that the cerebellum (1) computes sequences of *patterns* that predict future states of affairs in movement and thought, (2) does this by learning *internal models* of the *patterns* in the physical and internal worlds that first produce primitive physics in the infant (Vandervert, 2015, 2016), and (3), in a second tier (the phonological loop of working memory) of distillation of this primitive physics (and all subsequently derived physics), learns internal models behind the origin and manipulation of the *patterns* of mathematics (shape, motion, behavior, and "number"). Specifically, this chapter lays out newer cognitive neuroscience findings on the functions of the human cerebellum that describe the computational mechanisms of silent (below conscious awareness) *inner speech* within working memory in the cerebro-cerebellar system (Vandervert, 2020b). These computational mechanisms will be used to directly support Abbott's (2013) view that mathematics is not a mystery but is a product of simplified models of reality in human "imagination" (in both movement and thought). In collaboration with the cerebral cortex, mathematics, the science of patterns, is the product of (1) the cerebellum's fundamental sequence (or pattern) detection of internal and external events and (2) the cerebellum's optimization (through constantly error-corrected patterning) of prediction (Akshoomoff et al., 1997; Leggio & Molinari, 2015).

A corollary to the foregoing larger purpose of this chapter is to offer an explanation for difficulty in developing what Stanislas Dehaene (2001) called *number sense*. Dehaene used the term number sense "as a shorthand for our ability to quickly understand, approximate, and manipulate numerical quantities" (2001, p. 16), and number sense will be limited to that meaning for the purposes of this chapter. Dehaene (2001) made a strong point of the speedy "intuitive" nature of number sense: "I collectively refer to those fundamental elementary [numerical] abilities or intuitions as number sense" (p. 16). He attributes this quick, intuitive character of number sense to specifically evolved brain regions of the cerebral cortex. However, it will be shown how these elementary abilities or intuitions for number might be more parsimoniously and more definitively be explained by the above-described cerebellum-driven mechanisms of unconscious sequence learning.

A Note on the Traditional Attribution of Number Sense to the Intraparietal Sulcus Region of the Cerebral Cortex

It is important to note before moving on to a discussion of the broader background of cerebro-cerebellar coordination that the cerebro-cerebellar approach does *not* necessarily conflict with mathematics or number sense models that focus on brain functions associated with especially the intraparietal sulcus region of the cerebral cortex (for example, see Dehaene, 2001; Dehaene et al., 1999). Rather, the cerebro-cerebellar approach brings to bear additional brain mechanisms that provide more detailed and more comprehensive explanations for (1) the initial learning of number and its manipulation and (2) the subsequent, ongoing optimization and increased complexity of the neural patterns that constitute both mathematics and number sense. It will be seen in the next section that the cerebro-cerebellar approach provides these same advantages in all areas of the movement and thought in the cerebral cortex. For these reasons, a discussion of these strictly cerebral cortex-based models would be beyond the scope and space limitations of this chapter.

The Recent Evolution of Cerebro-cerebellar Coordination Toward the Learning and Optimization of Mental Processes

To help understand the arguments of this chapter on how the brain creates mathematics and number sense, it will be helpful to review research on cerebro-cerebellar collaboration toward the learning and optimization of mental processes. In their watershed articles, Leiner et al. (1986, 1989) began by noting that the human cerebellum increased three- to fourfold in last million or so years. They further pointed out that this huge increase in size of the cerebellum included the further evolutionary development of two-way nerve tracks (20 million on each side of the brain) linked to the cerebral cortex, including the parietal and prefrontal areas for planning and language functions (Leiner et al., 1989). Within this cerebro-cerebellar framework, Leiner, Leiner, and Dow proposed that the evolutionarily differentiated development of the newer part of the cerebellum's dentate nucleus (the *ventral* dentate) enabled the brain to unconsciously manipulate *ideas and their communication* with great dexterity just as the phylogenetically older portion of the dentate nucleus (the *dorsal* dentate) had done for motor skills. Today, such unconscious manipulation of ideas in the newer ventral dentate has been referred to as unconscious internal speech processes that enhance verbal working memory (Gilchrist & Cowan, 2010; Marvel & Desmond, 2010a, b, 2012).

Leiner et al.'s (1986, 1989) foregoing early speculations and hypothesis concerning the cognitive functions of the cerebellum have been strongly supported by literally hundreds of brain-imaging and clinical studies. Among such studies particularly relevant to the present chapter are the following: Akshoomoff et al. (1997), Balsters et al. (2013), Ito (1993, 1997, 2011), Leggio and Molinari (2015), Liao et al. (2014), Marvel and Desmond (2010a, b), Schmahmann (1997), Stoodley et al. (2012), Strick et al. (2009), and Van Dun et al. (2016). Van Dun, Manto, and Mariën provide particularly salient background on the error-corrective prediction via language functions of the cerebellum.

Figure 3.1 illustrates the enormous, 69-billion-neuron computational capacity of the cerebellum compared to 16 billion neurons in the cerebral cortex (Lent et al.,

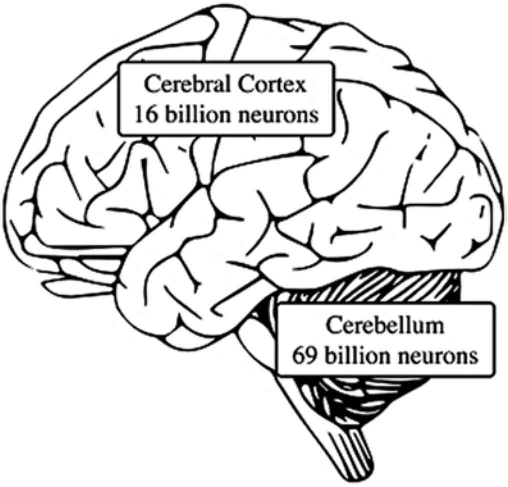

Fig. 3.1 Illustration of the cerebellum in relation to the cerebral cortex along with their respective neuron counts

2012) that, through generation after generation of repetitious (or practiced) behavior and thought and thereby constantly advancing skills and mental models, is proposed to have been and continues to be behind the evolution of uniquely human culture, including language and mathematics.

In humans, the ventral dentate is twice as large as the dorsal dentate and is proportionately larger than that of the great apes (Bostan et al., 2013). Marvel and Desmond (2010a) suggested that the newer ventral dentate (cognitive loop) was naturally selected *from* the evolutionarily older dorsal dentate (motor loop) as the cerebellar cortex and frontal areas of cerebral cortex expanded over the last million years. The ventral dentate of the cerebellum outputs to the frontal and parietal areas of the cerebral cortex (working memory, executive functions including planning, and rule-based learning).

Via the dentate nucleus, then the cerebellum is involved in the learning of countless internal models that are sent to the cerebral cortex for both motor and cognitive processing. Based on extensive research studies, Bostan et al. (2013) argued that the "signal from the dentate to the prefrontal and posterior parietal areas of the cortex [working memory, executive functions and rule-based learning] is as important to their function as the signal the nucleus sends to motor areas of the cerebral cortex" (p. 3). Thus, as a 69-billion-neuron strong computational system based on sequence detection and prediction (Leggio & Molinari, 2015), the human cerebellum wields an "unconscious presence" in thought, behavior, and affect. As Bostan, Dum, and Strick intimated above, the cerebellum's cognitive influence on prefrontal and posterior parietal areas of the cerebral cortex is commensurate with the immense learning requirements and apparently unlimited potential of the initiation and products of culture as proposed by Vandervert (2016), and, in this chapter, of mathematics. We will return to both the cerebellar mechanism of sequence detection and to the yoked ontogenetic cerebellar dorsal-to-ventral dentate development as they apply to all forms of movement and cognition and to the origin of mathematics in some detail in later sections of this chapter.

The Cerebellum Provides a Common Predictive Control to Movement and Cognitive Processes (Including Mathematics) in the Cerebral Cortex

Through the repetition of movement and cognitive skills (including imaginative thought), the human cerebellum learns progressively more efficient *internal models* of movement and mental processes that are going on in the cerebral cortex (Ito, 1993, 1997, 2011; Stoodley et al., 2012; Strick et al., 2009). The importance of curiosity-driven repetition cannot be overstated. Remember what Maryam Mirzakhani told us at the beginning of this chapter: "You have to spend some energy and effort to see the beauty of math." These cerebellar internal models consist of *distilled or compressed patterns* of the movement/thought sequences repeatedly taking place in the cerebral cortex. How this "distillation" first takes place in cerebellar models during infancy will be described in later sections of this chapter. See Fig. 3.1 for a recent neuron count and computational capacity of the cerebellum.

During the foregoing distillation process, movement and cognitive skills are reduced in the cerebellum to a common computational language of sequences or patterns that the various specialized areas of the cerebral cortex have evolved to translate toward optimal future behavioral and thought control (Akshoomoff et al., 1997; Leggio & Molinari, 2015; Vandervert, 2015, 2016). With repetition, these more efficient cerebellar models, operating below the level of conscious awareness, are to the cerebral cortex to bypass the original arduous, time-consuming cerebral cortical circuits; the cerebellar models make all movement/mental skills smoother, quicker, and progressively more error-free (Doya, 1999; Ito, 1997, 2008). The cerebellar models are also *blended within and across* skills (Imamizu et al., 2007; Yomogida et al., 2004) wherever it will make them more efficient and will allow them to *predict* complex movement/mental requirements before they occur (Akshoomoff et al., 1997; Leggio & Molinari, 2015). These efficiency effects of cerebellar internal models on goals formulated in the cerebral cortex are seen in any repeated activity. This includes everything from the progressively more expert skills in playing basketball, musical performance, solving math and engineering problems, and so on. This cerebellar prediction process will be described in detail in a moment.

Breakthrough Evidence of the Manipulation of Numbers (Arithmetic) in Cognitive Areas of the Cerebellum

As stated earlier in the purposes section, this chapter extends the learning of cerebellar internal models to an explanation of (1) the workability of mathematics in the real world, to (2) the manipulation of numbers (arithmetic), and to (3) the origin of number sense (fluidity or automaticity in number use and understanding). Directly in this regard, and following in the vein of the foregoing long line of discovery of the cognitive functions of the cerebellum began by Leiner et al. (1986, 1989), Hayter et al. (2007) conducted an imaging study on the involvement of the cerebellum in arithmetic calculation in verbal working memory. Hayter et al. used the Paced Auditory Serial Addition Test (PASAT) where subjects sequentially added the last two numbers in an overall sequence of five numbers. During this number addition task in verbal working memory, it was found that Crus VII in the cerebellar cortex along with prefrontal and parietal areas of the cerebral cortex were involved in *automated* counting. Hayter et al. concluded the following:

> We suggest that the cerebellar activation reflects the *automated simulation* [italics added] of cognitive operations [in cerebellar internal models] that are initially reliant on interactions between prefrontal areas, and that interaction between prefrontal areas and their targets is simulated [in internal models] within the circuitry of cerebellar cortical lobule VII.
>
> One salient characteristic of the PASAT is the relatively high demands it places on information [number] management. Numbers must be held in working memory, added to previously heard numbers, and then replaced by the next number. This task clearly requires participants to maintain and manipulate [number] information within working memory. (2007, p. 950)

Hayter et al. (2007) clearly showed cerebellar cognitive involvement in automated number manipulation in verbal working memory. However, in this very early work on the cerebellum's role in working memory and number manipulation, Hayter et al. did not provide specific analyses of the component phases of working memory (encoding, maintenance, and retrieval) or of inner speech.

The Ultimate Foundations of Number and Mathematics

Physics (Beginning in the Infant)

In attempting to understand the fundamental nature of mathematics, Eugene Wigner, who was quoted at the beginning of this chapter, and Derek Abbott (2013) began by discussing the history of the interlacing of mathematics with physics, the latter (especially its regularities) being our scientific contact point with "reality." A similar approach will be taken here. Only here it will be done from the point of view of the cerebro-cerebellar loops in the brain and their development of the awaking of the movement and cognitive processes that come to know about physics and mathematics in the first place, namely, the infant's first and continuing foundational operating system of *working memory*.

Working memory in this chapter consists of the merging of two theoretical models of working memory. First is Baddeley's (1992, 2000) model that includes (1) a central executive (control of attention), (2) a visual-spatial sketch pad, (3) a phonological or speech loop, and (4) an episodic buffer that links the other components in temporal sequences and connects them with long-term memory. Together, these four components constitute an operational description of current ongoing conscious states during any sort of problem solving including imagination. Second, to answer the question of how and in what cognitive framework, exactly, problem solving and imagination occur, Cowan (2014) argued that working memory is the "cauldron" for *concept formation* and that, within this cauldron, "the binding of ideas occurs more specifically in the focus of attention" (p. 210). By "binding," Cowan is referring to the joining of existing concepts together to form new concepts. Within the context of these models of working memory (Baddeley, 1992, 2000; Cowan, 2014), the interrelated phylogenetic and ontogenetic development of working memory is articulated in some detail in Vandervert (2011, 2015).

The Origin of Mathematics in the Brain: The Cerebro-cerebellar Basis of Patterns Leading to Mathematics in the Working Memory in Homo *sapiens*

Vandervert and Moe (2021) argued that the evolution of stone-tool making required detailed, precise differentiations of degrees of kinematics (movements) and dynamics (forces) in ToM among Homo *sapiens*. They based this argument on Stout and Hecht's (2017) following description of the intense repetitive social learning requirements that guided natural selection toward Homo sapiens over the last approximately 1.7 million years:

> 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. 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 required to achieve perceptual-motor competence. This requires mastery of relationships, for example between the force [dynamics] and location of the strike and the morphology, positioning [collectively, kinematics], 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. (pp. 7862–63).

Research has shown that it is now quite reasonable 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 social learning of internal models in the cerebellum (Ito, 1997, 2008; Van Overwalle et al., 2019).

Vandervert (2020a, b, c) and Vandervert and Moe (2021) proposed that the foregoing specific capacity for the cerebellar learning of the kinematics and dynamics provided the basis for the infant's leaning of its first concepts (image-schemas or conceptual primitives). In turn, these first concepts provide the basis for the child's later development of kinematic and dynamic degrees of differentiation for the phonological loop's capacity for social cognition of ToM in the cerebellum that includes the patterns of mathematics including number sense.

In this regard, Vandervert (2011, 2015, 2016) has argued that the most detailed behavioral/cognitive account that can be used to describe how the infant first builds working memory is the considerable research of Mandler (1992a, b, 2004, 2012). She proposed that the infant's *repetitive* patterns of *noticing* aspects of its own bodily movement in relation to objects moving in the environment (the relationships among objects, space, and time) are "*distilled*" or *"condensed"* (1992a) into *conceptual primitives*. (By "primitive," Mandler meant foundational and did not mean unstructured but structured.) Mandler further proposed two mechanisms that indicate that this noticing and distillation by the infant constituted the beginning of the construction of working memory: (1) noticing/distillation were the result of "an *attentional mechanism* [italics added] dedicated to simplifying spatiotemporal information" (2012, p. 426) and (2) noticing/distillation form the basis of an *accessible conceptual system* (1992b, p. 273). For both Baddeley (1992) and Cowan (2014), executive *attention* and *access* to conceptual information (via the episodic buffer) are the theoretical earmarks of working memory.

Figure 3.2 illustrates Mandler's characterizations of such "spatiotemporal" conceptual primitives she derived from her extensive experiments with infants. According to Mandler (2004), the conceptual primitives shown in Fig. 3.2 form the foundational basis of potential *consciously accessible visual-spatial meanings* for later relational thought and language.

Since, according to Vandervert (2003, 2015), Mandler's conceptual primitives (1) are driven into existence by attentional processes in the infant and (2) are accessible visual-spatial meanings, Vandervert (2015) argued that, together, they form the initial central executive and *an initial slave componen*t of the infant's working memory. In other words, Vandervert proposed that when put in sequential motion by attentional control processes, the conceptual primitives in Fig. 3.2 provide the infant with a *visual-spatial* working memory. Following Mandler's above theoretical premises, Vandervert (2011) proposed that as the infant develops toward childhood, the visual-spatial meanings (Fig. 3.2) are *blended* in the cerebellum with the infant's vocalizations in the process of language acquisition.

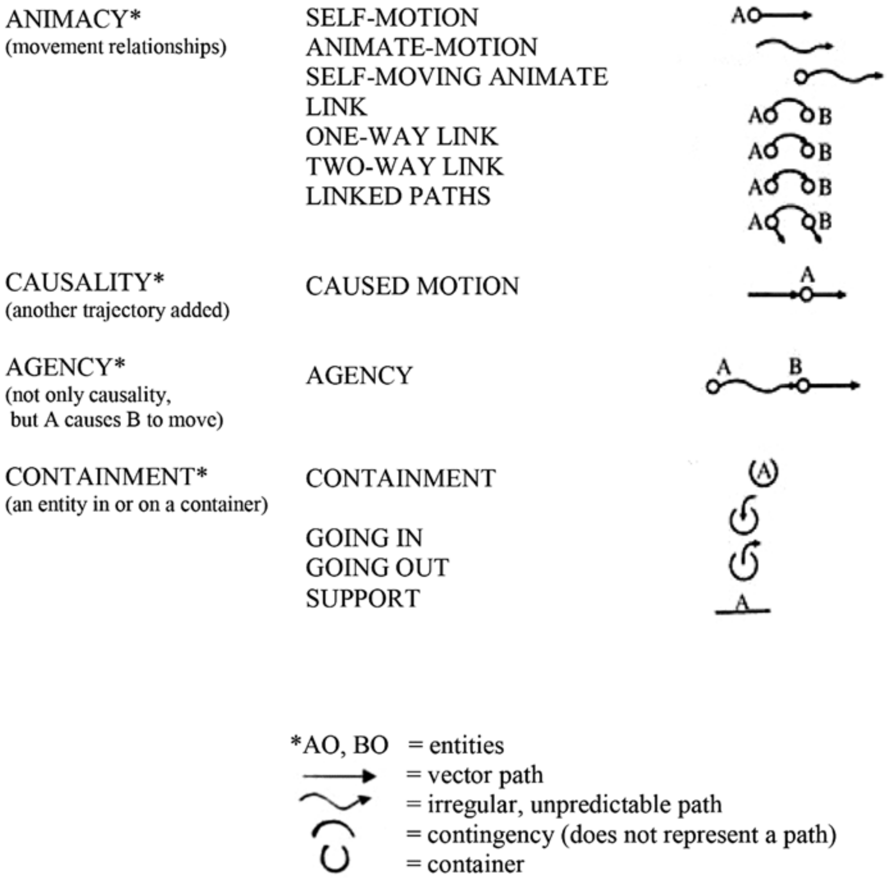

Fig. 3.2 Mandler's conceptual primitives—collectively, the infant's unconscious "primitive physics"

Mandler's Conceptual Primitives Are Cerebellar Internal Models That Can Make Predictions About Future Events

As described earlier, it is widely understood that *practiced* improvement in number calculation (or in anything else practiced) would be learned as constantly error-corrected internal models in the cerebellum (Akshoomoff et al., 1997; Ito, 1997, 2008; Leggio & Molinari, 2015; Leiner et al., 1986, 1989). It is proposed that for the learning of the predictive (anticipatory) value of Mandler's conceptual primitives (Fig. 3.2) in the cerebellum, Akshoomoff et al.'s (1997) following findings provide strong support:

> The cerebellum is a master computational system that adjusts responsiveness in a variety of networks to obtain a prescribed goal. 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* [italics added] 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* [italics added], very short time-scale, anticipatory information. (p. 592)

Akshoomoff, Courchesne, and Townsend's foregoing account of cerebellar sequence detection is in agreement with Leggio and Molinari's (2015) sequence detection process described earlier but is presented separately here because it clearly sets out the learning of an unconscious (or "intuitive") basis for predictive forward control.

Vandervert (2015) argued that Mandler's conceptual primitives are encoded as cerebellar internal models of visual-spatial working memory in the infant in accordance with both Akshoomoff et al.'s (1997) and Leggio and Molinari's (2015) cerebellar sequence detection process. Within this framework of the early growth of working memory, it is proposed that because it specifies "inferences of higher-order processes cognitive elaboration or social cognition cerebellar," the sequence detection hypothesis proposed by Leggio and Molinari (2015) is highlighted:

> According to this [sequence detection] hypothesis, the cerebellum detects and simulates repetitive patterns of temporally or spatially structured events, regardless of whether they constitute sensory consequences of one's actions in motor planning, expected sensory stimuli in perceptual prediction, or inferences of higher-order processes (e.g., *cognitive elaboration* [italics added] or social cognition). The simulation allows internal models to be created that can be used to make predictions about future events that involve any component, such as the *body, other persons, and the environment* [italics added]. (p. 36)

That the infant cerebellum encodes such body/environment predictive internal models as Vandervert (2015, 2016) proposed is supported by the following recent research. First, visual-spatial working memory begins to be established by six months of age (Zelazo et al., 2008). Second, the growth of neural networks for working memory in the infant are the same as those in older children and adults in connecting frontal, parietal, and temporal regions of the brain (Short et al., 2013). Moreover, Knickmeyer et al. (2008) argued that the 240% increase in the size of the cerebellum in the first year suggested the following:

> Because the cerebellum is critically involved in motor coordination and balance (Bastian, Hatch et al. 2002) the striking cerebellar growth may underpin the rapid motor developments of infancy. The cerebellum has also been implicated in a plethora of other cognitive abilities including planning, set-shifting, language abilities, abstract reasoning, *working memory* [italics added], and *visual-spatial organization* [italics added] (Schmahmann & Sherman, 1998). Given that "cognitive" regions of the cerebellum have reciprocal projections with nonprimary frontal, parietal, and occipital association cortex [50], the extremely rapid growth of the cerebellum in the first year may be a prerequisite for specific aspects of later cortical development. (p. 12180)

To support this "prerequisites-for-later-cortical-development" argument, it is suggested that the *transition* from visual-spatial working memory toward unconscious inner speech in early developing verbal working memory draws upon the same regions that support motor preparation and planning but not overt motor execution as found for unconscious inner speech in adults by Marvel and Desmond (2010a), namely, the premotor cortex, pre-SMA, and superior cerebellum (Lobule VI and Crus I). This contention is strongly supported by Liao et al. (2014) who subsequently found that, indeed, nonverbal (pictorial) information draws upon these same motor regions. Mandler's idea that later, consciously accessible language concepts are built from the infant's visual-spatial conceptual primitives (Fig. 3.2) therefore squares well with Knickmeyer et al.'s (2008) suggestion that the unparalleled growth of the cerebellum in infancy is a prerequisite for the later cognitive development of specific regions of the cerebral cortex.

Vandervert (2015) proposed that the *sequence detection process* described by Akshoomoff et al. (1997) and Leggio and Molinari (2015) (above) is, in fact, the mechanism of the distillation process described by Mandler as noted above. That is, cerebellar sequence detection produces the neural patterning that constitutes the physical world of the infant that we, through additional later-developed internal models, come to know as the "laws" of physics.

Again, it is critically important to note here that Mandler's (1992b) conceptual primitives are proposed to be the foundations of symbol systems:

> 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* [italics added] 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 [alternatively, Mandler refers to these as conceptual primitives]. These early representations are part of the symbolic function in the sense that they are meanings which symbols (gestures, images, or words [or numbers, it is proposed]) refer to or evoke. (p. 277)

It is important to note that Mandler (1992a) further proposed that movement dynamics (which she referred to as "animacy") were enfolded via the infant's scanning into the image-schemas depicted in Fig. 3.2. Vandervert (2011) proposed that each movement and thought is brought toward optimization and the prediction of future events a la Akshoomoff et al.'s (1997) cerebellar sequence detection.

Bringing together Leggio and Molinari's (2015) above cerebellar sequence detection toward *cognitive elaboration* and Mandler's transition from visual-spatial physics toward verbal working memory, we can perhaps see the cerebro-cerebellar basis of Maryam Mirzakhani's "…fascination for describing the geometric and dynamic complexities of curved surfaces—spheres, doughnut shapes and even amoebas—in as great detail as possible" described at the beginning of this chapter. Through repetition, the sequence detection-driven cognitive elaboration Leggio and Molinari described turned this deep fascination with visual-spatial surfaces (beginning in infant cognition in all of us) into mathematics.

Based upon the foregoing cerebellar learning and optimization of patterning in the conceptual primitives (the bases for symbol system), it will now be argued that mathematics and physical laws are products of the computational mechanisms of the human cerebellum and that physical laws are, indeed, the result of the cerebellum's distillation of the features objects moving in space. Figure 3.2 illustrates the conceptual primitives first learned in infancy and, collectively, constitute a foundational, rudimentary physics (Vandervert, 2015).

The Beginning of the Patterning That Becomes Mathematics and Number in the Cerebro-cerebellar System (A Second Phonological Tier of Cerebellar Abstraction)

Through cerebellar distillation, the conceptual primitives shown in Fig. 3.2 are of course *abstractions* based on many repeated perceptual/movement/tactile scans by the infant of its environment. That is, the primitives in Fig. 3.2 don't apply/represent particular situations or events but rather apply to all such situations and events in general. However, this is only the beginning point of abstraction or, as Mandler (1992a) put it, "distillation." That is, it is a *first tier* of abstraction from which, it is proposed, "number" (the cerebellar basis of mathematics) is concomitantly derived as a second tier of abstraction in the phonological loop, that is, through the same above repetitions, mapped onto the first tier. This idea is very strongly supported by research that indicates the evolution of the second-tier phonological loop from the cerebro-cerebellar blending of visual-spatial working memory and vocalization (Vandervert, 2019, 2020a, b).

It is further proposed that "number sense" (fluidity or automaticity in number use and understanding) is a product of the fluidity of the manipulation of cerebellar dynamics and inverse dynamics internal models related to this second tier of abstraction or distillation. This idea is strongly supported by Hayter et al.'s (2007) findings that number manipulation is automated in the cerebellum. We will return to the concept of number sense as a unique product of cerebellar *inverse dynamics models* in the next section.

The Adaptive Value of the Second Tier (Number) of Cerebellar Abstraction

The explanation of the adaptive value of this second or phonological tier of cerebellar abstraction is as follows. It is proposed that to efficiently predict complex future states within the framework of Leggio and Molinari's (2015) earlier-quoted sequence detection process (and thereby provide selective advantage in the struggle for survival), the cerebellum must not only learn distilled models of the objects (entities, paths, containers) kinematics and dynamics seen in Fig. 3.2 but must also distill models of the differing *numbers* of entities or persons (or predators) and the dynamics of environments (paths, containers, collectively escape routes) and their relevant *dimensions* (size, length, etc.). That is, it is suggested, within the framework of the apt title of Leggio and Molinari's article on cerebellar sequence detection, namely, "Cerebellar Sequencing: A Trick for Predicting the Future," numbers of entities and their kinematics and dynamics are as important to predicting complex future circumstances among numbers of objects (and thereby survival) as are the objects themselves. Again, this idea is very strongly supported by research that indicates that infants discriminate differing numbers of objects (Mandler, 1992b; McCrink & Wynn, 2004; Vanmarle, 2013).

The Cerebellar Mechanism That Differentiates the Concept of "Number" from Collections of Objects

The Cerebellar Origin of "Number" in the Abstract

But how is "number" in the abstract sense differentiated from collections of objects and their dimensions? Ito (1993, 1997, 2008) convincingly argued that when movements and thoughts are repeated (this would of course include the infant's repetitious observation and interaction with objects moving in space), they are learned as cerebellar *dynamics and inverse dynamics* models and that these dynamics models learn not only the individual trajectory actually practiced but generalize for application to quite different (and faster) trajectories of movement and thought.[1] Accordingly, it is proposed that when cerebellar dynamics models of numbers of objects and motions are learned, they likewise *generalize* (as do movement trajectories) not to just numbers of animals, objects, and motions, etc., but to numbers of "anything." That is, through the mechanism of cerebellar dynamics modeling of both movements and thoughts about objects and motions, when fed forward to the frontal and parietolateral association areas of the cerebral cortex (Ito, 1993), the concept of "number" becomes an unconscious/potentially conscious entity in itself. Thereby, numbers can then be applied to imaginary circumstances involving object moving through space. Through accumulated cerebellar optimization of such imagined circumstances, for example, the often-imagined circumstances that eventually led to Einstein's special theory of relativity (see Vandervert (2015) for detailed account of Ito (1993) applied to Einstein's own descriptions of his intuitive discovery), new mathematics may constantly emerge. It is suggested that this world of cerebellar dynamics and inverse dynamics models, when sent below the level of conscious awareness to the cerebral cortex, constitutes the aspects of the human "imagination" that, at the beginning of this chapter, Abbott (2013) theorized was the source of mathematics.

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[1] A detailed explanation of the theoretical basis and description of dynamics and inverse dynamics cerebellar internal models is beyond the scope of this chapter. The interested reader may consult Ito (1993, 1997) for easy-to-understand descriptions of these terms related to both movement and thought.

The Cerebellar Origin of "Number Sense" in the Child

How is the cerebellar modeling of "number sense" differentiated from cerebellar modeling based on the conceptual primitives illustrated in Fig. 3.2 that lead to phonological development in verbal working memory? Ito (1993) further points out that cerebellar dynamics models versus cerebellar *inverse* dynamics models assist the cerebral cortex differently and are controlled by different parts of the cerebellum:

> A dynamics model built into the paravermis-interpositus division of the cerebellum enables the motor cortex [or other areas of the cerebral cortex] to direct limb movement [or nonmotor functions] without peripheral feedback. By contrast, an inverse dynamics model built into the hemisphere-dentatus division of the cerebellum replaces the controller task of the motor cortex [or nonmotor areas of the cerebral cortex], rendering the control more automatic and less conscious. Hence, after repeated exercise, one become able to move [or think or calculate] quickly, precisely and smoothly without conscious thought. (p. 449)

It should be noted that the entire point of Ito's above article was to argue extension of the learning of cerebellar dynamics and inverse dynamics models to mental functions. For more detail, the reader is encouraged to consult also Footnote 1.

Fluidity in Number Sense

Thus, it is suggested that the development of *fluidity* in number sense is more reliant on *inverse dynamics* models (because they result in more automatic or intuitive performance), and phonological development in working memory is necessarily more reliant on dynamics models (because it requires constant updating throughout the course of thought or social exchange). It is hypothesized that since the learning of *inverse dynamics* models first requires the learning of *dynamics* models (1993) and then further requires continued levels of practice (specifically with number tasks in the case of the development of number sense), inverse dynamics models are more difficult to learn for some children depending on, for example, the child's history of exposure to learning number operations or his/her executive capacity in working memory to continue their focus attention on repetitive tasks.

The cerebellar modeling of the additional features of number, dimensions, and motion related to processes of imagination applies in common across all of the primitives and their mutual relationships seen in Fig. 3.2. *This secondary, more abstract distillation, it is proposed, becomes the basis of mathematics as we come to consciously know it (through phonological manipulation in working memory) and develop it through additional scientific and technological models, and their constant elaborations.* Accordingly, during both the advancement of societies and the enculturation of each individual (Vandervert, 2015), this phonological tier of largely cerebellar inverse dynamics modeling (mathematics) is constantly unconsciously elaborated in cerebellar inverse dynamics models of each individual as generations of children learn accumulations of science, technology, and so forth in school, occupations, and professions of society. These advanced cerebellar models are examples of what (1) Leggio and Molinari (2015) were referring to in their cerebellar sequence detection hypothesis as "inferences of higher-order processes (e.g., cognitive elaboration or social cognition)" (p. 2) and (2) Van Overwalle et al. (2019) referred to as predictive forward control within social cognition. It is further suggested that in prehistory, this foundational basis of mathematics in the cerebellum only became *conscious* rudimentary "mathematics" when blended from multiple cerebellar internal models (Imamizu et al., 2007) with other cultural requirements for, for example, learning the sequence of steps in the making of composite tools, in the enumeration related to the stringing of shells that might have culturally shared significance, or, in children, the demands of enculturation, including of course, in modern times, schooling (Vandervert, 2011).

Pattern Detection and Optimization: The Neural "Machine" Behind the Intuitive Aspects of Mathematics and Number Sense

What Exactly Happens in Working Memory During the Development of Number Sense?

How, exactly, would the cerebellum be involved in the development of number sense and/or the working memory of finger calculation? Marvel and Desmond (2010a, 2010b, 2012) have shown that silent inner speech (speech that may not reach consciousness) in the cerebellum indicates central executive control of verbal working memory manipulation of tasks. In such working memory tasks, they found the executive control in cerebellar inner speech to be associated with *motor planning and preparation related to encoding and retrieval* of task information (Marvel & Desmond, 2010a). Specifically, they found that encoding information into working memory increased dorsal dentate (motor) activity in the cerebellum while in the retrieval phase of working memory activity increased in the cerebellar ventral dentate (cognitive). In their conclusion, they proposed that:

> The cerebellum enhances working memory by supporting inner speech mechanisms. This capability emerged from overt speech and motor systems as an evolutionarily adaptive way to *boost cognitive processes* [italics added] that rely on working memory, such as language acquisition. (2010a, p. 7)

In a review of the cerebellum and nonmotor functions, Strick et al. (2009) strongly supported this facilitative (and elaborative) role of cerebellar inner speech in working memory. They suggested that the cerebellum is recruited whenever people engage in inner speech "to represent, maintain and organize task-relevant information and conscious thoughts" (p. 426), including in, for example, verbal working memory.

How Cerebellar Inner Speech Accesses Number Sense

But how does unconscious inner speech in the cerebellum *boost* cognitive processes in verbal working memory as Marvel and Desmond (2010a) proposed? Moreover, what is the underlying *cerebellar mechanism* that drives its unconscious inner speech "to represent, maintain and organize task-relevant information and conscious thoughts" (Strict et al., 2009, p. 426)? What was/is its evolutionary *adaptive* mechanism?

To answer this question, it is proposed that what Marvel and Desmond (2010a) refer to above as cerebellar *motor planning and preparation* is evolutionarily adaptive in boosting cognitive processes because, as in all skill development, cerebellar inner speech is driven by Akshoomoff et al.'s (1997) and Leggio and Molinari's (2015) cerebellar sequence detection process as described earlier in this chapter. That is, Marvel and Desmond's motor and *planning and preparation* is in actuality a succinct and equivalent way of describing Akshoomoff et al.'s and Leggio and Molinari's *prediction and anticipatory system adjustments*. The precise planning (anticipatory) mechanism that is evolutionarily adaptive can be readily appreciated by paraphrasing Akshoomoff et al.'s (1997) sequence detection scenario within the context of Marvel and Desmond's above-cited conclusions on the role of cerebellar inner speech as follows:

> Inner speech in the cerebellum boosts executive processes in working memory by *encoding ("learning") temporally ordered sequences* of multi-dimensional information about external and internal events *(effector, sensory, affective, mental, autonomic)* [italics added], 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 [italics added], very short time-scale, anticipatory information* [italics added]. (Paraphrased by combining Akshoomoff et al. (1997, p. 592) with Marvel and Desmond (2010a)

Evidence That Boosts in Fluency in Number Sense Occur in Inner Speech of Verbal Working Memory in the Cerebellum

As describer earlier in this chapter, Hayter et al. (2007) conducted imaging research on the involvement of the cerebellum in arithmetic calculation in verbal working memory. Recall that Hayter et al. used the Paced Auditory Serial Addition Test (PASAT) where subjects sequentially added the last two numbers in an overall sequence of five numbers. During this number addition task in verbal working memory, they found that Crus VII in the cerebellar cortex along with prefrontal and parietal areas of the cerebral cortex were involved in automatic counting.

Discussion and Conclusions

It is proposed that the computation of patterning in internal models in the cerebellum is predominantly responsible for creating our knowledge of physical realities, laws, and numbers. This view offers a neuroscience solution to (1) Eugene Wigner's (1960) puzzlement concerning "The Unreasonable Effectiveness of Mathematics in the Natural Sciences" and, at the same time, (2) an explanation that coincides with Derek Abbott's (2013) view that mathematics originates in human thought. That is, the cerebellum is the predominant source of patterning that becomes mathematics, the science of patterns. Evidence that the ultimate origin of mathematics and number is principally cerebellum driven in the cerebro-cerebellar system is based on the evolution of the 69-billion-neuron computational power of cerebellar internal models, operating below the level of conscious awareness, to constantly organize and optimize everything going on in the cerebral cortex and ultimately to produce our models of physical reality, number, and mathematics.

The Cerebro-cerebellar Approach Does Not Conflict with Traditional Brain Models of Mathematics and Number Sense

Importantly, it is pointed out that the cerebro-cerebellar approach does *not* necessarily conflict with mathematics or number sense models that focus on brain functions associated with especially the intraparietal sulcus region of the cerebral cortex, for example, Dehaene (2001), Dehaene et al. (1999). Rather, the cerebro-cerebellar approach brings to bear additional brain mechanisms that provide more detailed and more comprehensive explanations for (1) the initial learning of number and its manipulation and (2) the subsequent, ongoing optimization and increased complexity of the neural patterns that constitute both mathematics and number sense. In this regard, two explanatory advantages are immediately evident: (1) the "intuitive" character of number sense (Dehaene, 2001) can be parsimoniously and definitively explained in terms of unconsciously learned internal models in the cerebellum, which are then sent to the cerebral cortex, and (2) number sense in lower animals (Dehaene, 2001) can likewise be parsimoniously and definitively explained in terms of unconscious internal models learned in animal cerebella, which are then sent to their respective degree of development of their cerebral cortices.

Within this cerebro-cerebellar framework, it is suggested that (1) during infancy, the cerebellum learns a first tier of internal models based on the infant's perception and movement that results in a primitive physics that constitutes the foundations of visual-spatial working memory; (2) at the same time, a second (and more abstract inner speech comprising the phonological loop of verbal working memory) tier of cerebellar *inverse* dynamics models based on the first tier (physics) learns number and relationships among dimensions across those primitive physics of the first tier;

and (3) "number sense" originates largely below the level of consciousness in the cerebellar *inverse* dynamics models described in (2). This general view is strongly supported by findings that the cerebellum automates the manipulation of number information (Hayter et al., 2007). Further, developing from this conceptual structure of internal models, the cerebellum's developing inner speech both boosts verbal working memory capacity and enhances executive control processes in that working memory, and silent speech-enhanced executive control in verbal working memory (Marvel & Desmond, 2010a, b, 2012) facilitates the learning of inverse dynamics models related to the development of number sense.

The foregoing framework for the ultimate origin of number and mathematics involves cerebro-cerebellar loops between the cerebellum on the one hand and the frontal and parietal regions of the cerebral cortex on the other (Marvel & Desmond, 2012); however (and this is critically important), the ultimate origin and creative expansion of number and mathematics is driven principally by the predictive, error-corrective *sequence detection mechanism* in the cerebellum (Akshoomoff et al., 1997; Leggio & Molinari, 2015). This prominent role of the cerebellum would be supported by cerebro-cerebellar loops connecting at least two somatotopic finger representations in the cerebellum and inner speech-driven finger counting/calculation that produces parallel, mutually strengthening and sequentially structured motor traces to *boost* (not originate) the manipulation of numbers in verbal working memory.

Essay Questions for Psychology Achieves the Impossible: The Social Origins of Mathematics

1. In reviewing the accomplishments of Maryam Mirzakhani, how would visual-spatial working memory in the infant form a basis for a mathematics of complex surfaces?
2. Could a person consciously know about mathematics with the phonological loop of working memory?
3. According to Baddeley et al. (1998), what is the critical job of the phonological loop?

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Chapter 4
The Prominent Role of the Cerebellum in the Origin of Intertwined Social and Technological Cumulative Culture

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M. Manto et al., *The New Revolution in Psychology and the Neurosciences*,
https://doi.org/10.1007/978-3-031-06093-9_4

Abstract In the context of observational social learning during stone-tool making beginning over 1 million years ago, it is shown how early humans unconsciously learned intertwined social cognition and technology as elements of cumulative culture. To support this idea, the predictive, cerebellar mechanism of socialization and capacity for technological advancement toward the norms of culture is shown to be sequence detection in cerebellar internal models, which are sent to the cerebral cortex to solve problems. It is shown how diminished observational learning among children who experience early life in orphanages or excessive television viewing results in lower grades, poor socialization, and diminished executive control in working memory. It is concluded that the essential components of cumulative culture are learned and sustained not by the cerebral cortex alone, as many traditionally believe, but are learned through repetitious improvements in prediction and control by internal models in the cerebellum. Following this perspective, new explanations of cumulative culture are discussed: (1) how internal models are blended to produce the creative, forward advances in cumulative culture; (2) how the recent evolutionary expansion of the cerebellum was involved in the coevolution of earliest stone tools, socialization, and technology—leading to the origin of cumulative culture, and (3) how excessive television viewing may represent a cultural shift that diminishes the observational learning of internal models of the behavior of others and thus may result in a mild, parallel version of Schmahmann's cerebellar cognitive affective syndrome.

The Silent Social-Technological Power of the Cerebellum
During the prehistoric time of its operation, the complex organization of stones at Stonehenge silently detected the sequences of movements of the earth in relation to celestial bodies, which were moving along their own trajectories. These interrelated sequences constituted fundamental predictive models of the timing of critical hunting, agricultural, religious, and related social events. The timing provided by these *predictive* models "signaled" the people of the surrounding society to undertake the necessary practices and thinking, which would lead to survival and make the culture constantly more efficient.

Must-Read Quick Overview for All Students

Stonehenge is pictured at the beginning of this chapter to set the stage for an important, far-reaching question. As you read through the chapter, please be thinking about what that question might be. Pay close attention to the meaning of cumulative culture and the role the cerebellum plays in the intertwining of social and technological advances. Along this line, you might be surprised at what Sigmund Freud had to say about the origins of technology in relation to parts of the body. In thinking about how the cerebellum optimizes solutions to problems and what the cerebral cortex does with these optimizations, ask yourself how cerebellum-to-cerebral cortex optimization accelerates the advance of cumulative culture.

Cumulative Culture

Vandervert (2016, 2018, 2019, 2020a, b, c) proposed that, during human evolution, cerebellar internal models were optimized through practice and, when sent back the cerebral cortex, were blended toward creativity in working memory. Further, Vandervert and Moe (2021) proposed that this evolution of cerebellum-to-cerebral cortex blending thereby led to progressive developments in higher levels of social cognition as described by Van Overwalle et al. (2019), intertwined with technological discovery which together undergird culture (Vandervert, 2016). This view of the social/technological evolution of culture squares completely with extensive work as described by Stout and Hecht (2017), who are leading researchers in neuroanthropology (the study of brain evolution in culture). At the beginning of their article titled "Evolutionary Neuroscience of Cumulative Culture," Stout and Hecht provided an insightful description of the progressive development of the brain and the constant accumulation of culture:

> Modern humans live in a culturally constructed niche of artificial landscapes, structures, artifacts, skills, practices, and beliefs accumulated over generations and beyond the ability of any one individual to recreate in a lifetime. Like the air we breathe, this *cumulative cultural matrix* [italics added] is so immersive that it is easy to forget it is there. However, this is the medium through which we grow, act, and think, and it exerts profound influences on human life across a range of behavioral, developmental, and evolutionary scales. How did our species find itself in this remarkable situation? (p. 7861)

To answer this question Stout and Hecht went on to propose that the evolution of stone-tool making provides a strong scientific way to understand the accumulation of culture.

> One solution is to seek inspiration from the archaeological record of human evolution. As the name implies, this early "Paleolithic" evidence is dominated by stone tools. These artifacts are valuable, not only because they endure but because they provide prolific and fine-grained evidence of behavioral changes across a critical evolutionary interval during which hominin brains tripled in volume to assume their modern proportions. Stone tools were key components of premodern subsistence and survival strategies and likely helped to shape the very course of this evolution. (p. 7862)

The term *cumulative culture* refers to the fact that across generations, culture constantly develops toward more and more advanced and complex social and technological forms. As Stout and Hecht (2017) put it above, cumulative culture includes advances that are "...beyond the ability of any one individual to recreate in a lifetime" (p. 7861). In addition, it can be seen from the first of Stout and Hecht's above quotes that cumulative culture includes the topics studied by psychology: That is, they point out it is "the medium through which we grow, act, and think, and it exerts profound influences on human life across a range of behavioral, developmental, and evolutionary scales." In their second quote, they assert that stone tools "provide prolific and fine-grained evidence of behavioral changes across a critical evolutionary interval during which hominin brains tripled in volume to assume their modern proportions."

Purpose

The purpose of this chapter is to describe further research evidence for the prominent role of the cerebellum in the intertwined evolution of social cognition and technology and to provide examples of this intertwining in widely known social-technological history. It will be seen that the term "cumulative" in cumulative culture has been (and is) the work primarily of the learning and refinement of internal models in the cerebellum, which are sent to the cerebral cortex for execution in thought and movement.

To clearly illustrate the intertwining of social learning, and obviously concomitant technological learning in making stone tools, Stout and Hecht (2017) described in detail how "high fidelity" social learning (e.g., involving theory of mind (ToM) of others) takes place between learners and teachers (and *took* place for roughly 1.7 million years between ancient learners and teachers):

> 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. 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 [between learner and teacher], 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. Novel behaviors are copied by breaking them down into familiar action elements (e.g., lift, turn, twist), matching these, and reassembling. (pp. 7862–63)

A careful reading of Stout and Hecht's (2017) above quote reveals the key moments driving the natural selection of the cerebra-cerebellar system high-fidelity social learning toward the control and prediction of the kinematics (movements) and dynamics (forces) of what we now call physics and the basis of technology. Thus, Stout and Hecht's above stone knapping scenario constitutes the evolutionary intertwining of social cognition and technology as it underlies cumulative culture. It is suggested that the reader carefully examine Stout and Hecht's (2017) above quote to determine phrases that (1) portray kinematics and, on the other hand, that portray dynamics and (2) where they are characterized as social and where they are characterized as technological.

The Observational Learning of Cerebellar Internal-Models Provides the "Glue" for Socialization and Technological Advances

In the sharing of the above cumulative advance of new, creative blends of cerebellar internal models across individuals, observational learning is critically important. Observational learning is learning that occurs by observing how others do things. Observational learning is critically important during socialization today but was even more important among ancient peoples, where the bulk of socialization occurred, not in schools with books and computers but in everyday community and family activities (including often-repeated religious/political ceremonies and rituals) and in technological apprenticeships. How are cerebellar internal models acquired through observational learning and, specifically, how are they *accumulated* in a person-to-person manner that leads to advances in culture?

In answer to this question, Wolpert et al. (2003) proposed that a high level of "control" and observational learning related to the nonverbal social and technology-related behavior and intentions of others can be based on cerebellar internal models learned from one's own motor system:

> We hypothesize that…during action observation the motor system [one's own motor system] can be used to understand the actions of others. This could be an efficient process because our CNS has learned [on the basis of cerebellar internal models sent to the cerebral cortex] to predict the consequences of actions on our own body [as a collection of controlled objects] and this can be used to make accurate predictions about others. (p. 597)

Along this line of observational or imitative learning, cerebellum research has outlined detailed accounts of how internal models of communication between speakers and listeners and in the imitation of others operate in (1) advanced social interaction at the symbolic level (Wolpert et al., 2003); (2) higher-level, mutual mental modeling between speaker and listener during social interaction (Imamizu & Kawato, 2009); and (3) the comprehension of sentences between speaker and listener (Moberget et al., 2014). It will be seen below that, taken together, these findings strongly support Van Overwalle et al.'s (2019) proposal that the cerebellum sends theory of mind (ToM) forward, predictive control to the cerebral cortex for the refinement of social cognition and stone-tool making (and other technology construction).

In summary here, it is proposed that it is cerebellar internal models, learned largely through observational learning that provides the substance and "glue" that binds individuals together in both the experience and capacity to participate in a common culture and provides the basis for cumulative culture. Leggio and Molinari (2015) provided strong evidence that sequence detection is the process that builds cerebellar internal models:

> According to this hypothesis, the cerebellum detects and simulates repetitive patterns of temporally or spatially structured events, regardless of whether they constitute sensory consequences of one's actions in motor planning, expected sensory stimuli in perceptual prediction, or inferences of higher-order processes (e.g., cognitive elaboration or social

> cognition). The simulation allows *internal models* [italics added] to be created that can be used to make predictions about future events that involve any component, such as the body, other persons, and the environment. (p. 36)

Without the concepts initiated by cerebellar internal models through repetitious learning of common tasks in each individual's brain, there would be no conscious/unconscious common framework to bind the members of culture together in a "silent" fashion, again, for example, in art, science, religion, music, mathematics, technology, child-rearing, and so on. The expression that members of culture are bound together in a "silent" fashion is used here to draw attention to this important point that Leiner, Leiner and Dow (1989) made on the unconscious nature of learning in the cerebellum:

> Cerebellar signals are always generated below the level of conscious awareness in the brain. How cerebellar contributions can improve the speed and skill of cerebral performance is therefore not accessible to conscious introspection. Rather, the cerebellar contributions to cognitive and language skills would constitute a part of what is called 'the cognitive unconscious.' (p. 1006)

Strong Support for the Cerebellum-Driven, Stone-Tool Origin of Social Cognition and Intertwined Technological Advancement

It is helpful to repeat here that Vandervert (2018, 2019, 2020b) argued that the process of natural selection that occurred during over a million years of the stone-tool knapping scenario provided above by Stout and Hecht (2017) led in great part to the three- to fourfold increase in the size of the cerebellum and to a broadening of the cerebellum's functions in relation to the cerebral cortex. Vandervert described how, notably, these broadened functions included social cognition, working memory expansion, and technological innovation and creativity.

Strong support of these arguments can be seen in Van Overwalle et al.'s (2019) description of how the cerebellum is involved in social cognition:

> 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* [italics added], 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. (p. 35)

Autobiographical knowledge refers to one's fluent or automatic knowledge (including abstract knowledge) of past and future action/interaction sequences related to the self (Martinelli et al., 2013). The importance of autobiographical knowledge to technological advancement will be described below.

Cerebellum-to-Cerebral Cortex Blending During Creativity Leading to Acceleration of Cumulative Culture

Van Overwalle et al.'s (2019) forward controller function can be directly connected with the cerebellum's internal modeling of advances in new forms and levels both of social cognition and of technology. Specifically, Imamizu et al. (2007), and Imamizu and Kawato (2009) have shown that when people are confronted with new situations, the learning of cerebellar internal models is modified in ways which produce solution outcomes unfamiliar to the learner. These researchers concluded that when confronting new situations or simply practicing or mulling over old problems, internal models are sent to the cerebral cortex, where they are blended toward optimization in new ways. It is important to note that once a blend occurs in the cerebral cortex, the cerebellum then learns an internal model of that new blend, optimizes it further, and sends it back to the cerebral cortex, thus constantly upgrading and accelerating the quality of creative solutions to the original problem. This cerebellum-to-cerebral cortex positive feedback loop, along with people sharing new ideas with one another, can explain why the pace of cumulative culture accelerates. (A positive feedback loop may be understood as follows: When output of the system is feedback, it increases the magnitude of the quality and/or quantity of the loop's next output and so on.) It is proposed that these new solution outcomes that are unfamiliar to the learner are what is traditionally called creative "intuition." Imamizu et al.'s (2007) research thus provides valuable insight into how, through cerebellar blending, central executive control in working memory might "elaborate" toward intuition in extended cases, where the scientist (or anyone) is struggling with the development of new ideas or new technology.

In expanded summary, within the framework of social/technological cumulative culture as described by combining Stout and Hecht's (2017) stone-making and Van Overwalle et al.'s (2019) forward control social cognition, the following three-part unconscious cerebrocerebellar mechanism can be proposed to be behind the production of progressively higher-level contributions to cumulative culture. *First*, through the detection of sequences in repetitive patterns during problem-solving, the cerebellum unconsciously learns error-driven *internal models* of all behavioral, social, cognitive, and affective processes that subsequently contribute to goal attainment in *working memor*y, and it uses these internal models to *adaptively* optimize the unconscious prediction and anticipation of similar future environmental events. This first mechanism is based directly on Akshoomoff et al.'s (1997), and Leggio and Molinari's (2015) (quoted earlier in this chapter) mutually supportive conclusions on the predictive, forward modeling role of the cerebellum in both movement and cognitive control processes. Cerebellar internal models are learned as neuronal circuits for the "forward-predictive" manipulation (control) of what in the cerebellum literature is referred to as a "controlled object." As Leggio and Molinari point out in their earlier quote, such controlled objects have been found to include the body (e.g., in using the hands, legs, arms, movement of the eyes, and emotional expression), other persons (e.g., in "controlling" the behavior of others in communicating, teaching, negotiating, and so forth), and the environment (e.g., everything from using stone tools to playing the piano to accessing information from iPhones). Thus, with repetitious practice, forward-predictive internal models in the cerebellum permit the unconscious manipulation of the forgoing controlled objects toward the achievement of goals. We will return to this learning of predictive cerebellar internal models in relation to socialization toward cumulative culture as described earlier by Stout and Hecht (2017) in more detail later in this chapter.

Second, within the foregoing framework of cerebellar sequence detection and prediction process, unconscious cerebellar forward-predicting internal models are adaptively *blended* (Imamizu et al., 2007) in new prediction-optimizing ways during all problem-solving, for example, in cumulative culture components: religious social interaction, technology, mathematics, and science (Vandervert, 2015). *Third*, when the resulting unconsciously learned new blends of forward-predicting internal models are sent to consciousness in working memory in the cerebral cortex, they are often experienced as sudden insight or intuition (Vandervert, 2015). Once sent from the cerebellum to the cerebral cortex, these new blends of forward-predicting internal models may both advance the individual's learning of the task at hand and contribute newly expanded knowledge in the form of innovation and creative discovery, again for example, in social interaction, mathematics, science, and technology. This overall three-part *cerebro-cerebellar* mechanism of innovative and creative advancement may be summarized in the phraseology Leggio and Molinari (2015) so aptly suggested in the title of their above-quoted article on cerebellar sequence detection, namely, "Cerebellar Sequencing: A Trick for Predicting the Future."

Thus, the sequence-detecting cerebellum constantly optimizes the prediction-anticipation of future social behavioral and cognitive requirements. And, when these optimizations in movement and thought result in intuitively experienced advancements in the manipulation of aspects of the environment such as advancements in stone-tool technology, cerebellar sequencing is a "trick," not only for predicting the future but, at the same time, also for "manufacturing" the future that henceforth includes, for the first time, the accumulation of that stone-tool technology. That is, prediction-anticipation leads to the imitative copying or *projection* of motor, sensory, and mental processes into the form of adaptive technologies, which become part of the future environment around which the accumulation of culture is shaped.

A Note from Sigmund Freud

An interesting and unexpected source of clarification of the meaning and outcome possibilities of cerebellum-to-cerebral cortex collaborative imitative copying and projection of the kinematics and dynamics of the bodies of ourselves and others can be seen in Sigmund Freud's (1930) *Civilization and Its Discontents*.[1] Freud proposed that beginning with stone tools, the development of the technological aspects of cumulative culture has amounted to advantageous amplifications of the functions of our motor, cognitive, and sensory systems. The first sentence of the following Freud quote captures its overarching point:

> If we go back far enough, we find that the first acts of civilization were the use of tools…*With every tool man is perfecting his own organs* [italics added], 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 suggests that all tools are further-refined or more powerful copies or projections of our own motor, sensory, and working memory brain functions. And, in the same way Freud suggests that "writing was in its origin the voice of an absent person," cave drawings can be seen as the images of missing or revered animals or persons. And, in the case of modern painters such as Picasso, who sought to reveal dark contents of the unconscious mind in his work, highly abstract cerebellum-to-cerebral cortex blending of imaginative images can be seen. (Recall the discussion of cerebellum-to-cerebral cortex blending presented earlier in this chapter.) Moreover, if Freud had conceived this 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 list of "man's" social and technological amplifications of motor, sensory, and mental functions greatly. Surely, he would have expanded his mentions to include the problem-solving of everyday computers, voice synthesizing and recognition, and the manipulation of language, social cognition, mathematics, and technological storage in, for example, iPhones and robotic systems. These too, of course, are imitative projective extensions of our cerebellum-to-cerebral cortex functions. Following Freud's view, was/is perhaps Stonehenge an amplified imitative projection of cerebro-cerebellar sequence detection?

Beginning with stone tools, anticipation, projection, and amplification are what cerebro-cerebellar collaboration has evolved to do; it perfects and removes the limitations of the motor, sensory, and cognitive functions of our own organs. And the evolutionarily adaptive value of this imitative projection of our own organs is that it enhances prediction-anticipation into longer timescales and into added dimensions and extremes of those environments—they collectively constitute cumulative culture.

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[1] The inclusion Freud's insightful contribution here is not meant to imply support for other portions of this particular 1930 work of Freud.

An Expanded Historical Review of Research on Cerebro-Cerebellar Basis of Cumulative Culture

In their two watershed articles, Leiner et al. (1986, 1989) pointed out that the human cerebellum increased three- to fourfold in size and had developed new neural projections (pathways) to the prefrontal and association areas of the cerebral cortex in the last million years. Based on this enormous increase in size and the new connections with the highest cognitive areas of the cerebral cortex Leiner et al. (1986) convincingly argued that the cerebellum had thereby evolved beyond its traditionally thought role only in the skillful manipulation of motor activity (movement) to the additional role of "the skillful manipulation of ideas" (p. 444). They further pointed out that this huge increase in size of the cerebellum is accompanied by 20 million nerve tracks on each side of the brain going *from* the cerebral cortex (including from the parietal and prefrontal areas for planning and language functions) *to* the cerebellum (Leiner et al., 1986, 1989). (By comparison, each optic nerve (there are two) running back to the visual areas of the brain has approximately one million nerve tracts.) In addition to these massive inputs *to* the cerebellum (40 million nerve tracts), there is a huge number of nerve tracts going *from* the cerebellum's *dentate nucleus* to the cerebral cortex (again, including *to* the parietal and prefrontal areas for planning and language areas) (Leiner et al., 1989).

The Evolutionary Expansion of the Dentate Nucleus

Most people reading this journal will not have heard of the *dentate nucleus*. However, the dentate nucleus provided Leiner et al. (1986, 1989) with a sort of evolutionary Rosetta Stone for deciphering the evolutionary history of the "leap" (in this case, imagine a slow-motion leap) from all things motor in apes to, in addition, all things cognitive (including language) in humans. Leiner et al. (1986) pointed out that the dentate nucleus differentiated during evolution from all motor-related nerve tracts in lower animals toward a combination of motor and cognitive nerve tracts in humans, the latter reaching intricately into the higher association areas of the cerebral cortex:

> In the human brain, the dentate nucleus has become enormous, both when compared to other cerebellar nuclei *and when compared with its size in other species* [italics added]…Its increase in size developed in parallel with the enlargement of the cerebral cortex [notably the uniquely human parietal and frontal areas] and cerebellar cortex. (p. 444)

In this regard, the human dentate nucleus is composed of a phylogenetically older motor loop (dorsal dentate) and a newer cognitive loop (ventral dentate). In humans, the ventral dentate is twice as large as the dorsal dentate and is proportionately larger than that of the great apes (Bostan et al., 2013).

Leiner et al.'s (1986, 1989) foregoing early speculations and hypotheses concerning the cognitive functions of the cerebellum and their account of the evolutionary transitional role between lower animals and humans of the dentate nucleus have been strongly supported by literally hundreds of brain-imaging and clinical studies. Among such studies particularly relevant to the present chapter include the following: Akshoomoff et al. (1997), Balsters et al. (2013), Ito (1997, 2011), Leggio and Molinari (2015), Liao et al. (2014), Marvel and Desmond (2010, 2012), Schmahmann (1997), Stoodley et al. (2012), Strick et al. (2009), and Vandervert (2015, 2016, 2020a, b).

As illustrated in earlier chapter of this book, Fig. 4.1 illustrates the enormous 69 billion-neuron computational capacity of the cerebellum compared to 16 billion neurons in the cerebral cortex (Lent et al., 2012) that Vandervert (2016) proposed was and continues to be behind the evolution of uniquely human culture.

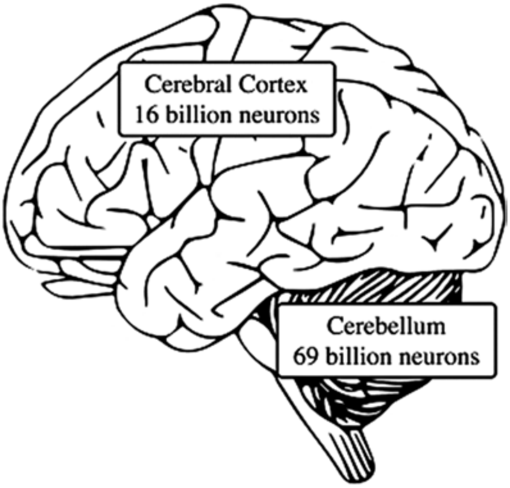

Fig. 4.1 The number of neurons in the cerebellum versus the number in the cerebral cortex. (Neuron count data from: Lent et al., 2012)

In this regard, Marvel and Desmond (2010) suggested that the ventral dentate (cognitive loop) was naturally selected from the evolutionarily older dorsal dentate (motor) as the cerebellar cortex and frontal areas of cerebral cortex expanded over the last million years. The ventral dentate of the cerebellum outputs to the frontal and parietal areas of the cerebral cortex (working memory, executive functions including planning, and rule-based learning) (Ito, 1997; Leiner et al., 1986; Strick et al., 2009). Through the dentate nucleus, then, the cerebellum is involved in the learning of countless internal models, which are sent to the cerebral cortex for both motor and cognitive processing. Based on extensive research studies, Bostan et al. (2013) argued that the "signal from the dentate to the prefrontal and posterior parietal areas of the cortex [working memory, executive functions and rule-based learning] is as important to their function as the signal the nucleus sends to motor areas of the cerebral cortex" (p. 3). Thus, as a 69 billion neuron-strong computational system based on sequence detection and prediction (Leggio & Molinari, 2015), the human cerebellum wields an "unconscious presence" in thought, behavior, and affect that is commensurate with the immense learning requirements and apparently unlimited potential of the experience and products of culture.

Additional Insight into the Collaborative Roles of the Cerebellum and the Cerebral Cortex in Social Cognition and Technology

Doya (1999) rigorously laid out the differences between the computational architectures of the cerebral cortex and the cerebellum. He argued that (1) the computational role of the cerebral cortex is *context-dependent*, essentially managing survival and maintenance operations in the conscious here-and-now context; and (2) the computational role of the cerebellum, on the other hand, is *context-independent*, which means, in accordance with Leggio and Molinari (2015), the cerebellum learns internal models of control that bypass the rigorous relearning of the requirements of hear-and-now contexts by establishing feedforward models of behavior and thought to unconsciously predict, anticipate, and deal with those repetitive situations. These context-independent computations produce forward-predicting cerebellar internal models, which enable skillful, error-corrected manipulative control in everything from, for example, skillful sports performance to expert piano performance to the creative ideas and innovations that result from *repetitive* experience in science, technology, religion, mathematics, art, music, daily routines, and social relationships (Vandervert, 2015; Vandervert et al., 2007). These are the components of cumulative culture.

How, exactly, are we to understand Doya's (1999) analysis of these different but completely integrated roles of the cerebral cortex and the cerebellum? How does "context-independence" come about and to what and where does it apply? As described earlier in the Introduction section of this chapter, Akshoomoff et al. (1997), and Leggio and Molinari (2015) independently proposed that the cerebellum does indeed specialize in learning of unconscious, forward-predicting internal models that are sent to working memory and other sensory, motor, and affective processes in the cerebral cortex. Akshoomoff et al. (1997) described important detail on how the cerebellum builds a predictive, unconscious structure into its internal models:

> The cerebellum is a master computational system that adjusts responsiveness in a variety of networks to obtain a prescribed goal [in Baddeley's 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. This may require the cerebellum to implement a succession of precisely timed and selected changes in the pattern or level of neural activity in these diverse networks [It would do this my learning internal models that would implement such changes.]. 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 timescale anticipatory processes medi-

> ated by cerebral systems, output of the cerebellum provides moment-to-moment, unconscious, very short timescale, anticipatory information. (pp. 592–593)

It is important to note here that *attentional control* as used in the context of this chapter refers to its learning within working memory in cerebellar internal models as described in the above quote by Akshoomoff and Courchesne et al.—see also Vandervert (2015) in this regard.

Thus, combining Doya's (1999) description of the differences between the computational architectures of the cerebral cortex and the cerebellum with Akshoomoff, Courchesne, and Townsend's above cerebellar sequence detection, "context-independent" refers to internal models learned in the cerebellum that replace the *original context* of *repetitious* learning required of any tasks, including difficult, time-consuming, higher-order cognitive tasks and task related to complex social interaction (the original "contexts"). For example, in relation to the original, often arduous context-dependent process of learning a complex musical piece, "context-independent" does *not* mean independent of the musical piece in question but rather independent of the original difficult, repetitive learning tasks that have been replaced by a template of internal models (neural circuits) in the cerebellum. In regard to such higher-order and social tasks, see particularly Doya (1999, p. 671); Akshoomoff et al.'s (1997) above-quoted listing of declarative memory, working, attention, arousal, affect, and so on; Leggio and Molinari's (2015) above-quoted listing of "inferences of higher-order processes" and "other persons" as controlled objects. As an example of the learning of context-independent internal models for these highest levels of thinking, Ito (1997) provided a straightforward discussion on how the cerebellum might learn internal models of complex mental models taking place in the parietolateral association area and then forward them back to the cerebral cortex to carry out the original context-dependent task in an error-corrected and unconscious manner.

It is proposed that, through cerebrocerebellar collaboration, these context-independent cerebellar internal models provide the basis for both the unconscious learning *of* and ongoing participation *in* culture and the *advance* of cumulative culture. The powerful *adaptive* value of such cerebellar context-independent internal models in culture is twofold: (1) they enable humans to collectively think or perform faster, more appropriately, and more consistently in a predictive, feedforward manner (Akshoomoff et al., 1997; Ito, 1997; Leggio & Molinari, 2015; Vandervert, 2015), and (2) increasingly adaptive and increasingly complex mental models and movements connected to complex ongoing social and technological problems with a culture can be creatively developed through the *blending* of cerebellar internal models in the individual (Imamizu et al., 2007; Vandervert, 2015; Vandervert et al., 2007).

Individuals then share the products of their new, creative blends of cerebellar internal models (new ideas, new technologies, and so forth) with other members of culture, thus advancing cumulative culture as a whole. These new ideas and technologies in turn give rise to additional new creative blends of cerebellar internal, thus continually advancing cumulative culture (often rapidly in the manner of a positive feedback loop) to higher social, scientific, technological, and artistic levels. An example of the optimization of mental/manual skill (point 1 in the paragraph immediately above) in many individuals throughout culture can be seen clearly in the process of learning cerebellar internal models through years of repetitive practice of the work of others, leading to errorless and seemingly effortless complex musical performance (Vandervert, 2015). Recall that "context-independent" does *not* mean independent of the musical piece in question, but rather independent of the original difficult, repetitive learning tasks that have been replaced by a template of internal models. Now, through these internal models, the pianist, for example, plays a complex concerto errorlessly without "thinking" about the original contexts of the practice sessions (see, e.g., Parsons et al., 2005). The leading edge and heart of cumulative culture is made up of many such highly practiced individuals across all components of culture, religion, science, art, engineering, music, technology, and so on. And it is proposed that examples of the constant, cumulative advance of ever-new blends of internal models and thus the advance of culture (point 2 in the paragraph above) include the cumulative growth of agricultural methods; the relentless technological and artistic advances of ancient Egyptians, Greeks, and Romans; and on into the likewise relentless technological and artistic advances of the modern world.

Important Implications of the Prominent Role of the Cerebellum in the Learning of Interwoven Social-Technological Cumulative Culture: Cultural Deprivation and Cultural Shifts and the Cerebellar Cognitive Affective Syndrome

The foregoing survey of the cerebellum's role in the learning of culture and cumulative culture offers a way to study the effects of cultural practices, cultural changes, and, importantly, cultural deprivation and maltreatment on the development of working memory. Along this line in regard to Schmahmann's (2004) idea of dysmetria of thought, Ito (1997) described how such changes might affect both normal and abnormal mental and affective development:

> In analogy to the contribution of the cerebellum to motor activity, its contribution to mental activity may be specified as regulating the speed, consistency, and appropriateness of cognitive processes, with dysfunction leading to a dysmetria of thought (Schmahmann, 1991). This provides theoretical bases for explaining cerebellar symptoms such as *dysmetria* [italics added] as being due to impairment of a cerebellar model of musculoskeletal system. A similar explanation applies to *mental dysmetria* [italics added] that may occur due to lack of the model [cerebellar internal model] which copies a mental model [of certain processes taking place in the cerebral cortex]. (p. 486)

Dysmetria refers to the loss of the sense of distance in relation to muscular actions associated with brain lesions. Specifically, in his analogy to dysmetria, Schmahmann (2004) proposed that such dysfunction of the cerebrocerebellar circuits/functions produces dysmetria of thought (and, social cognition as described by Van Overwalle et al., 2019) with the following mental and affective characteristics:

> It [the cerebellar cognitive affective syndrome] is characterized by (1) disturbances of executive function, which includes deficient planning, set-shifting, abstract reasoning, working memory, and decreased verbal fluency; (2) impaired spatial cognition, including visual-spatial disorganization and impaired visual-spatial memory; (3) personality change characterized by *flattening or blunting of affect and disinhibited or inappropriate behavior*; and (4) linguistic difficulties, including dysprosodia, agrammatism and mild anomia. *The net effect of these disturbances in cognitive functioning was a general lowering of overall intellectual function* [italics added]. (Schmahmann, 2004, p. 371)

It is proposed that these functions are importantly related to the early development of mental and affective components of communication (language and nonverbal communication) (a la Wolpert et al.'s, 2003 earlier above quote) by which, to a large degree, culture is learned and transmitted. This idea is supported by Knickmeyer et al. (2008) who argued that the 240% increase in the size of the cerebellum in the first year suggested the great sensitivity of the cerebellum to experience during the first year and on into the school years:

> Because the cerebellum is critically involved in motor coordination and balance (Bastian & Thach, 2002) the striking cerebellar growth may underpin the rapid motor developments of infancy. The cerebellum has also been implicated in a plethora of other cognitive abilities including planning, set-shifting, language abilities, abstract reasoning, *working memory* [italics added], and *visual-spatial organization* [italics added] (Schmahmann & Sherman, 1998). Given that "cognitive" regions of the cerebellum have reciprocal projections with nonprimary frontal, parietal, and occipital association cortex, the extremely rapid growth of the cerebellum in the first year may be a prerequisite for specific aspects of later cortical development. (p. 12180)

This "later cortical development" can be coupled with the development of social cognition as described earlier in this chapter by Van Overwalle et al. (2019). It is therefore suggested that through a number of types and degrees of cultural deprivation, the functions listed in Schmahmann's earlier above cerebellar cognitive affective syndrome may be impaired during socialization/enculturation.

Cultural Deprivation Impairs the Acquisition of Social Cues

Studies on the effects of socialization on the development of the cerebellum have offered preliminary support for this suggestion. For example, Bauer et al. (2009) studied the effects of cultural deprivation on the development of the cerebellum and cognitive functions of young children in austere orphanages. This research found that orphanage-induced social/cultural deprivation resulted in significantly smaller left and right superior-posterior cerebellar lobe volumes and, cognitively, reduced visual-spatial memory and reduced attentional and planning components of executive function. In addition, Baldacara et al. (2011) also found that emotional maltreatment during such institution-induced socialization leads to reduced cerebellar volume and to various degrees of the "flattening or blunting of affect and disinhibited or inappropriate behavior" cited among the symptoms of dysmetria of thought by Schmahmann (2004) above. All of the foregoing deprivations can be looked upon as diminished opportunities for one-on-one, hands-on interaction with other bodies as described earlier by Wolpert et al. (2003) in the context of observational learning. In this regard, following Van Overwalle et al. (2019) on social cognition and the cerebellum, Vandervert and Moe (2021) argued that mathematics acquisition in the early school year can be accelerated by increased one-on-one, hands-on teaching strategies.

In a similar vein, corroborative evidence that the cerebellum is the key driver of socialization and, thereby, enculturation also comes from a perhaps unexpected source. Giedd (2012) pointed out that electronic media (television, cellphones, the Internet, etc.) have changed the way children and adolescents learn, play, and socialize more in the 15 years before the study than in the previous 570 some years since the introduction of Gutenberg's printing press. Because the increase in the use of these media (mostly television, see Rideout et al., 2010) has dramatically changed learning, play, and socialization among children, it represents a definite and significant cultural modification or "shift." The actual existence of this suggested cultural shift is strongly supported by a preponderance of findings that, much like Bauer et al.'s (2009) and Baldacara et al.'s (2011) above-cited social/cultural deprivation-induced effects, excessive television viewing among children produces what might be considered mild, parallel appearances of Schmahmann's (2004) cerebellar cognitive affective syndrome. For example, studies on both excessive and specialized aspects of television viewing have found that those same (but less pronounced) negative attentional, executive, and affective effects occur (Lillard et al., 2015; Lillard & Peterson, 2011; Pagani et al., 2013; Watt et al., 2015). As Bauer et al. (2009) and Baldacara et al. (2011) found for institutional deprivation, these researchers suggested that excessive television viewing deprives young children of critical developmental socialization and peer-interactive play activities.

Learning to Be a Bystander: Excessive Television Viewing Reduces the Cerebellum's Learning of Other-Persons-as-Control-Objects

All of the foregoing research concludes that the negative effects of both institutional deprivation and excessive television viewing are the result of reduced opportunities for hands-on socialization. But how, exactly, does this reduced socialization occur in the brain? Within the framework of cerebellar internal models described in this chapter, it is suggested that these negative socialization effects are not only the result of the learning of a lessened degree of socialization but also the result of the learning of internal models for *a different kind of socialization*. Although this suggestion of a different kind of socialization can apply in either institutional deprivation or excessive television viewing, an example will be given only for the case of excessive television viewing. Again returning to Doya's (1999) and Wolpert et al.'s (2003) above notion of speaker and listener-as-control-objects in interpersonal language and nonverbal communication, it is proposed that when a child watches characters in scenarios on television (either cartoon characters or actual persons), they are still learning cerebellar internal models related to "socialization," but with increased television viewing, it is increasingly a *one-sided* or "bystander" template of internal models that is being learned rather than one of a socially richer two-sided interaction. This television-mediated, one-sided socialization is less demanding of the unconscious learning of cerebellar control models (e.g., requires less hands-on social give-and-take communication and eye contact) in the control of attention, executive control, and affect as described by Akshoomoff et al. (1997). This occurs in television viewing, as is suggested, because the other "persons" are either more predictable because television plots are very similar, or their behavior and thoughts need not be predicted at all because there are no real-world consequences if the television viewer does not learn to predict them. See Leggio and Molinari's (2015) quote on cerebellar predictive sequence detection above. In fact, the other persons or cartoon characters seen in television programming may be more entertaining, because they are *not* predictable, or prediction is elusive.

In essence, today's children in varying degrees are learning to be a part of a "media-mediated" culture that is quite different from that of previous generations. They are learning to become a part of the rapidly emerging electronic media culture described above by Giedd (2012). As Giedd suggested, some of the effects of what in this chapter is called one-sided socialization are positive (e.g., in opening new horizons of information access) and some are negative (as in lowering attentional control, school grades, and social adjustment as found by Lillard et al. (2015), Lillard and Peterson (2011), Pagani et al. (2013), and Watt et al. (2015). It is proposed that the negative effects are the result of mild impairment of the development of *implicit* learning via cerebellar internal models as described by Ito [12], leading to an equally mild, parallel development of Schmahmann's (2004) cerebellar cognitive affective syndrome (see component characteristics listed earlier above). This contention is supported by D'Mello and Stoodley's (2015) in comments on the role of cerebellar internal model in implicit learning, especially in early development:

> Abnormal connectivity between the cerebellum and cerebral motor regions might result in sub-optimal automatization and modulation of motor behaviors, and might also be related to delayed acquisition of gestures important for social interaction and communication. Similarly, abnormal connectivity between the cerebellum and cerebral cortical regions involved in language could lead to atypical organization of language networks in ASD, and be associated with delayed language acquisition in ASD. (p. 13)

Discussion and Conclusions

It appears that the essential components of the origin of culture and cumulative culture are learned and sustained not by the cerebral cortex alone, as many traditionally believe, but are substantially learned in cerebellar internal models through intertwined social and technological repetitive experience. These cerebellar internal models are then sent to the cerebral cortex for execution. Such cerebellar internal models were adaptive because of the following: (1) by learning temporally ordered sequences of multi-dimensional information about external and internal events, they predicted future events in advance; (2) through constant error-correction, they regulated the speed, consistency, and appropriateness of movement and thought in the cerebral cortex; and (3) when confronting new tasks, they are blended to provide both optimized and wholly new solutions. It is further suggested that, in the process of socialization, these cerebellar internal models are largely derived through observational learning from communication (including gestures) shared among members of closely interacting people. It is important to keep in mind that these cerebellar internal models are generated below the level of conscious awareness (Leiner et al., 1989) and, as it is suggested, are responsible for predicting behavioral and cognitive requirements necessary in the origin of culture, for the participation in culture, and the forward advance of cumulative culture.

It is concluded that the cerebellum-to-cerebral cortex approach to the nature and origins of cumulative culture offers the following new explanations for a number of important questions.

First, the larger neuroanthropological context for the evolution of the origin human cumulative culture now appears to have been the adaptive natural selection of sequence-based social-cognitive processes required in the likewise natural selection of the manufacture and use of stone tools beginning some one and a half million years ago (Stout & hecht, 2017). This social-technological adaptive selection of stone-tool manufacture and use likely selected toward the three- to fourfold expansion of the size and expanded connectivity with the cerebral cortex of the cerebellum and, and, functionally, its cognitive, working memory functions, which Leiner et al. (1986) referred to as “the skillful manipulation of ideas” (p. 444). Within this context of adaptively evolving cerebrocerebellar feedback loops and the slowly accelerating complexity of stone-tool production (Ambrose, 2001), the earliest shared, highly-repetitive, *observational learning* necessary for a cerebellum-driven social-technological cumulative culture would have likely developed. It is suggested that, within this highly-repetitive, sequential activity and based on the blending of cerebellar internal models in the cerebral cortex was the beginning of a *positive feedback loop* (what was learned and produced in turn led to greater, more refined leaning and production) for cumulative culture. This scenario is in direct agreement with anthropologist Ralph Holloway’s brain-culture positive feedback loop [20, pp. 293–295].

Second, Cerebellar internal models are blended in the process of optimizing problem-solving in working memory, and that when these newly blended internal models are sent to consciousness in the prefrontal executive and parietolateral association cortices (working memory areas), they may be experienced as sudden, intuitive new solutions to problems. Within the larger context of the first point above, this offers an explanation not only for individual creativity but the constant creative, forward advance of cumulative culture as a whole.

Third, the cerebrocerebellar approach to the origin and nature of cumulative culture described herein offers a brain-based explanation of how excessive television viewing (especially among children) might disrupt traditional, pretelevision, two-sided socialization, which reduces attentional control, school grades, and social adjustment. This cerebro-cerebellar explanation proposes that excessive television viewing diminishes social interaction with other-persons-as-cerebellar-control--objects (replaces “other persons” with noninteractive and therefore inconsequential “persons”) *and thereby reduces the repetitious or implicit aspect of observational learning*. It is suggested that this results in the learning of cerebellar internal models for a one-sided socialization that is similar in effect to that of socially abused children raised in socially austere orphanages (noninteractive caretakers, little play). As D’Mello and Stoodley (2015) suggested for implicit motor and cognitive learning especially during the early developmental years, it is further proposed that this one-sided, unconscious learning of cerebellar internal models results in diminished learning of attentional, executive, and affective functions, in other words, a mild, parallel learned version of Schmahmann’s (2004) cerebellar cognitive affective syndrome.

About Stonehenge

At the larger scale of understanding, how might we conceive of the role of the cerebellum in the brain’s overall thought processes and our manufacture of day-to-day interweaving of social cognition and technology? Can Stonehenge represent a simple yet fairly accurate thumbnail analogy of the cerebellum? Stonehenge was of course a “tool” directly in Sigmund Freud’s sense of the amplification of the body and mind, and, like a small, compact little Stonehenge at the back of the brain, the cerebellum has evolved as a “tool,” which perfects the prediction, timing, and skill or motor and cognitive functions of the cerebral cortex. The relationship between Stonehenge and the human cerebellum may therefore be more than a mere analogy—it may in fact represent a sort of evolutionary homology of the kind Freud suggests. As a homological extension of “the perfection of man’s organs” (to paraphrase Freud), the relationship between Stonehenge and the human cerebellum can help people from a broad variety of disciplines appreciate the role of cerebellum as a pivotal mechanism of uniquely human survival. This strongly suggest that just as Stonehenge organized and regulated the people of the Stonehenge culture, the cerebellum organizes and regulates the many cognitive, movement, and emotional areas of the cerebral cortex that produce cumulative culture.

At the same time, can this analogy between the cerebellum and Stonehenge shed light on what happens to the relationship between the cerebellum and the cerebral cortex when the cerebellum malfunctions? For example, what would be the effects on the Stonehenge society if the stones were knocked down or otherwise put in disarray? Would the effects on the society be similar to those a malfunctioning cerebellum might have on the practices and thinking of the cerebral cortex? Or would long-term memories of members of the society (the analogy to the cerebral cortex) enable the society to carry on the festivals, plantings, and harvesting pretty much as normal, with only minor changes in their optimum timing?

Psychology Achieves the Impossible: The Origin of Intertwined Social and Technological Cumulative Culture (Essay Questions)

1. What is cumulative culture?
2. How does the cerebellum prominently contribute to cumulative culture?
3. How might the functions of the cerebellum be related to the functions of Stonehenge?
4. What does cerebellum-to-cerebral cortex blending mean?
5. How does cerebellum-to-cerebral cortex blending form positive feedback loops toward innovation and creativity?
6. How do Sigmund Freud's comments on the origins of technology relate to cumulative culture?

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Chapter 5
From Motor Systems to Working Memory: The Origins of Stone Tools, Language, Culture, and Rise of Homo *sapiens*

Cherie Marvel

During working memory, motor traces are formed to represent the sequence of actions that would be necessary to rehearse the information held in mind without actual implementation of such actions, e.g., inner speech of phonemes to remember new words or planned actions to solve a puzzle. The cerebellum generates an internal model to represent the sequence of "actions" and, communicating with the cerebral cortex, adjusts the model with repeated practice, strengthening rehearsal of the information held in mind. [Illustration by Callum Bullers]

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M. Manto et al., *The New Revolution in Psychology and the Neurosciences*,
https://doi.org/10.1007/978-3-031-06093-9_5

Abstract The purpose of this chapter is to describe support for the prominent involvement of cerebellar internal models in the formation of the adaptive selection of motor planning and preparation, leading to the evolution of working memory. Within this framework, it has been suggested that (1) motor traces were created to prolong the duration in which information could be held in mind and (2) this process led to the formation of working memory and (3) cerebellar-guided internal models of the motor traces were iteratively improved and, when communicated to the cerebral cortex, updated working memory content. It is concluded that, through this process, working memory facilitated the formation of language and culture in Homo *sapiens*.

Must-Read: Quick Overview for All Students

In this chapter you are asked to understand how the manipulation of ideas in working memory arose from motor activity of early humans. The gist of what you should learn from this chapter is outlined in the following paragraphs.

Working memory is vital for basic functions in everyday life. Evidence from the field of cognitive neuroscience has shown that working memory is supported by the motor system and, in particular, by regions that are involved in motor planning and preparation, in the absence of overt movement [as in when one *imagines* how to accomplish a task]. These “secondary motor” regions are called upon to support working memory by generating internal motor traces that reinforce the representation of information held in mind. The primary aim of this chapter is to elucidate motor-cognitive interactions through the lens of working memory and to suggest that cerebellar-driven internal models helped to form the origins of human language and culture.

Look carefully for evidence that such secondary motor activity underlies both the everyday use of language and the evolution of language in the first place. Return to Chap. 1 of this book, and consider how Albert Einstein’s description of “thinking” fits into the idea that motor planning and preparation lead to language forms of that same motor activity.

The term inner speech has been defined variably in the literature. One common feature is that inner speech is inaudible. In this report, inner speech is broadly defined as internalized, inaudible verbal thought that may or may not reach conscious awareness and may or may not be accompanied by subliminal vocal activity. To a certain extent, our views concur with those of Vygotsky, who posited that inner speech would not resemble spoken language as we know it but would be compressed. Thus, inner speech may represent a variant of external speech but is not necessarily a direct emulation of it (i.e., speech without sound). Conceivably, though, inner speech engages a verbal code, drawing upon motor planning and preparatory brain regions that precede overt speech. [The foregoing paragraph is from Marvel & Desmond (2012, p. 43, left col.).]

Note: Students should imagine their own inner speech, i.e., their own silent speech that occurs in the privacy of their own thoughts.

Introduction

More than three decades ago, Leiner et al. (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. 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, these cerebrocerebellar interactions are usually thought to confer [only] a motor benefit on humans, such as increased dexterity of the hand. 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 [in] humans: the skillful manipulation of ideas. (p. 444)

Since the time of Leiner, Leiner, and Dow's classic proposal, this "skillful manipulation of ideas" has been extensively study by psychologists and neurologists as *working memory* (Baddeley, 1992; Marvel & Desmond, 2010, 2012, 2016; Marvel et al., 2019; Hayter et al., 2007).

Working Memory and the Motor System

Working memory involves the ability to hold information in mind, without reliance on external cues, in order to rehearse or manipulate that information. Working memory can be sustained as long as necessary, through updated rehearsal, as long as attention is continuous. With distraction, access to that information is disrupted. Cognitive neuroscience has revealed that the brain's motor system actively supports working memory functions (Marvel et al., 2019). It has been suggested that working memory substrates evolved from the existing, phylogenetically older motor system to create a redundant process to enhance cognition.

Visual and auditory memory is brief, on the order of 1–2 s. However, if such memories could be held in mind for longer durations, one could elaborate upon that knowledge, for example, by imagining it in novel ways. During evolution, this ability would have improved problem-solving skills and conferred an advantage to those who could best attain it. The motor system likely provided a way for early humans to prolong the duration of information held in mind, which led to the formation of working memory.

Motor planning and preparation regions of the brain, such as the premotor cortex, supplementary motor area, and cerebellar hemispheres, have been shown to activate just prior to activation within the primary motor cortex, which co-occurs with movement execution (Hulsmann et al., 2003). Motor planning and preparation neural activations, it is believed, represent the motor sequence for pending actions, and importantly, these "secondary" motor activations can be repeated until an action occurs. Thus, motor sequences for actions may be created without subsequent implementation. For example, motor planning brain regions might create a motor sequence, or motor *trace*, to represent imagined vocalizations, in the absence of overt speech. Similarly, motor planning regions might create a motor trace that represents a sequence of imagined movements (e.g., hand movements required to wave hello).

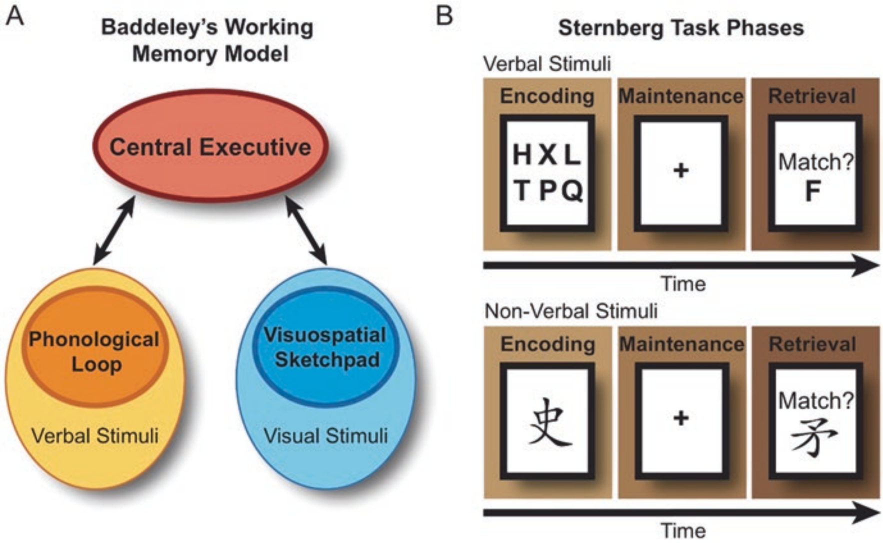
When vocalizations are held in mind, without outward expression, this can be thought of inner speech. It is inaudible and may or may not reach awareness. Inner speech likely represents a variant of external speech but is not necessarily a direct emulation of it (i.e., speech without sound). Conceivably, though, inner speech engages a verbal code, drawing upon motor planning and preparatory brain regions that precede overt speech.

Inner speech is evident when one tries to hold a long list of items in mind (e.g., recipe ingredients). One may become aware of "hearing" those items repeated in their head. This is a sign of the motor system's support of cognition. As working memory demands increase, the motor system's activity also increases (Marvel & Desmond, 2010, 2012; Marvel et al., 2012, 2019). If the list of items becomes very long, one may feel the need to repeat those items aloud. This is the motor system ramping up its efforts further to support cognition, and "regressing" to the primitive ways in which the motor system supported early forms of working memory, as overt speech. As working memory demands decrease, motor activity also decreases, and rehearsal again goes silent, as inner speech. [A similar support of cognition by the motor system would apply to the rehearsal of nonverbal content (e.g., visual image of writing a Chinese character by someone who does not know the language). For purposes of simplicity, however, this chapter emphasizes verbal working memory.]

Working Memory at the Operational Level

Baddeley (1992) developed a model which describes the details of the *operational* features of working memory. These operationally defined features of "components" of working memory allowed psychologists and neurologists to design controlled, measurable studies of working memory. Baddeley 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" (1992, 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 sketch pad, 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. These operational features of working memory provide a framework for understanding the capacity to manipulate ideas in working memory. For example, holding verbal information in mind over brief delays may have enabled the ability to combine brief vocalizations and attach them to symbolic meaning, supporting language development (Aboitiz et al., 2006). This framework, therefore, is important to understanding the evolution of language, thinking, problem-solving, planning, and creativity.

An overall description of the evolutionary emergence of the phonological loop was described by Baddeley et al. (1998). In brief, they proposed that "the primary purpose for which the phonological loop evolved was to store unfamiliar sound patterns while more permanent memory records are being constructed" (1998, abstract). Following the findings of Ashida et al. (2019), Castellazzi et al. (2018), and Saeki et al. (2013), it is reasonable to suggest that new, repetitious words would be error corrected and modeled in the cerebellum in relation to existing phonological working memory.



(a) Conceptualization of working memory composed by Baddeley consists of a central executive system that supervises a phonological "loop" and a visuospatial "sketch pad" to hold information in mind over brief periods (e.g., seconds). (b) Baddeley's model of working memory is often tested in the laboratory using the Sternberg task. The Sternberg task consists of three cognitive phases: (1) encoding of stimuli, (2) maintenance across a delay, and (3) retrieval of the stimuli to compare it with a probe item. The Sternberg task is compatible with both verbal and nonverbal stimuli. (From "How the motor system integrates with working memory," by Marvel et al., 2019. Copyright 2019 by Elsevier Ltd. Reprinted with permission)

A Synergistic Relationship Between Working Memory and Stone-Tool Making

Vocalizations that co-occurred with external cues would eventually become associated, leading to the formation of symbolic meanings. This foundation of language could be communicated to others who could, in turn, build upon those symbolic meanings and apply them to novel situations. This process would have been useful for communicating important information, such as environmental dangers and new skills. Similarly, covert vocalizations could also hold symbolic material, in the form of inner speech, to guide one's thoughts and actions.

During the evolution of stone-tool making, vocalizable or imitable symbols would have supported the transfer of knowledge of procedural memory (e.g., striking a stone with specified force), concept (e.g., creating a stone with a sharp point along the edge), and social cognition (e.g., making stone weapons pleases the group elders). Through repetition, these vocalizations and actions would have adaptively selected the phonological loop and visuospatial sketch pad within working memory.

Marvel et al. stated:

> Motor traces may be utilized in the maintenance of content that would be inefficient to represent by visual or acoustic means alone. For example, creating an internal trace of the motor sequences that would be necessary to read aloud visually presented letters—without actually saying them aloud—may strengthen memory retention of those letters more than simple visual representation of the orthographic images or acoustic representation of letter sounds would alone. Similarly, creating an internal trace of the motor sequences involved in drawing non-verbalizable symbols, without overtly drawing them, may prolong memory of that symbol far longer than would visual representation. (2019)

The latter example would have been especially important for goals such as stone-tool making, that is, to have a goal in mind and then attempt to create it (i.e., through stone-tool knapping).

Cerebellar Internal Models Advanced Primitive Speech Toward Sophisticated Language

Neural coding of internal models in the cerebellum would have played a major role in this evolutionary process. Recall that neural coding in cerebellar internal models is accomplished via cerebellar microcomplexes, which detect and correct movement (and cognitive) errors in order to optimize the repetitive skill learning at hand (Ito, 1997, 2008, 2011). Neural coding of cerebellar internal models related to stone-tool making could have included: (1) the role of inner speech in the phonological loop of working memory in such action (Alderson-Day & Fernyhough, 2015; Mariën et al., 2014; Marvel & Desmond, 2012; Marvel et al., 2019), (2) ramping up of repetitive inner speech in *difficult* tasks (Saeki et al., 2013; Marvel & Desmond, 2010, 2012; Marvel et al., 2012, 2019), and (3) cognitive and socially mediated skill development (Ito, 1997, 2008, 2011; Van Overwalle et al. 2019; Vandervert, 2018). Socially mediated skill development would have included the learned pairing between vocalizations (or actions) and outcomes that were created first by the teacher and then by the learner. The learner would have attempted to recreate those vocalizations (or actions) to generate the same outcome. In this way, stone-tool making, for example, would have induced evolutionarily pressure to augment the phonological loop (and visuospatial sketch pad) rehearsal mechanisms, which are based on secondary motor activations of planning and preparation processes.

Within this context, it can be argued that the detailed cause-and-effect relationships required in the cerebellar modeling of stone-tool making led to the iterative fine-tuning of existing internal models (Imamizu et al., 2007) and relied upon planning and preparation-related motor activity, coupled with both overt and inner vocalizations in working memory. This state of working memory likely existed in early humans approximately 1.7 million year ago with early intentional stone modification where it is estimated that technology levels became related to brain evolution (Stout & Hecht, 2017). Such primitive inner vocalization likely played all of the many different roles in working memory as appeared in the modern inner speech of Homo *sapiens* (see Alderson-Day and Fernyhough (2015) for excellent discussions of these roles of inner speech). Marvel et al. (2019) argued that these modern roles of inner speech in working memory were adaptively selected from such primitive roles.

In this regard, Vandervert (2018, 2019, 2020) suggested that this early stone era was the basis of the adaptive selection among cerebellar internal models from vocalization toward primitive speech and primitive inner speech. Cerebellar internal models for primitive inner speech would have adaptively increased the detailed quality of prediction of the effects of the stonework. In addition, primitive inner speech rehearsal during stonework would have helped retain constantly *new*, simple cause-and-effect relationships in memory (Vandervert, 2020) to improve knapping outcomes. Such an adaptive selection of "verbal" material from vocalization in early working memory is supported by Mariën et al. (2014).

This overall evolutionary scenario is strongly in sync with Baddeley et al.'s (1998) proposal that "the primary purpose for which the phonological loop evolved is to store unfamiliar sound patterns while more permanent memory records are being constructed" (abstract). Following more recent support from the findings of Castellazzi et al. (2018) and Mariën et al. (2014), it is reasonable to suggest that new, repetitious words would be error corrected and modeled in inner speech and neutrally coded with novel motor traces, guided by the cerebellum. That is, this newer evidence provides a direct neurological parallel to Baddeley, Gathercole, and Papagno's description of the purpose and operation of the phonological loop for acquisition of new word forms.

Conclusions

Working memory emerged from evolutionary pressures that selected toward holding information in mind for more than just a few seconds. This process likely drew upon the existing motor system, which involved motor planning and preparation mechanisms, that could be activated and reactivated indefinitely. Such motor traces represented the sequence of neural activity that would be needed to execute intended actions, even if those actions were never implemented. This process provided the neural underpinnings of sustained rehearsal for verbal and nonverbal content within working memory.

Cerebellar internal models enabled fine-tuning of these motor traces to make new working memory content (primitive or modern) faster, more consistent, and optimized toward the task at hand (Ito, 1997). Evolving verbal working memory, in particular, provided the critical adaptive advantage toward the emergence of language. It is suggested that without this internal modeling by the evolving cerebellum, the manipulation of ideas via working memory that is inherent in language-driven thought [as theorized by Leiner et al., 1986 at the beginning of this chapter] would not have evolved in the cerebral cortex to distinguish Homo *sapiens*.

Student Essay Questions

1. What is inner speech?
2. How does inner speech sustain or support working memory?
3. Give two examples of everyday motor planning and preparation in visual-spatial imagination.
4. Why would brief, often brilliant products of working memory be sustained by intricate motor activity? Hint: Consult Einstein's description of "thinking" in Chap. 1 of this book. Then, recognize that Einstein used his working memory to make mathematical models of his own imagined movement in space and time. Here's Einstein's imagination of movement at age 16:

   > How…could…a universal principle [underlying true physical laws] be found? After ten years of reflection such a principle resulted from a paradox upon which I had already hit at age of sixteen: If I pursue a beam of light with the velocity of *c* (velocity of light in a vacuum), I should observe such a beam of light as a spatially oscillatory electromagnetic field at rest. However, there seems to be no such thing, whether on the basis of experience or according to Maxwell's equations. From the very beginning it appeared to me intuitively clear that, judged from the standpoint of such an observer, everything would have to happen according to the same laws as for an observer who, relative to the earth, was at rest. For how, otherwise, should the first observer know, i.e., be able to determine, that he is in a state of fast uniform motion? (1949, p. 53)

   Einstein himself said of his intuitively derived paradox, "One sees in this paradox the germ of the special relativity theory is already contained" (Einstein, 1949, p. 53).
5. Why would ancient stone-tool makers have engaged in inner speech (or inner vocalization) while knapping stones, especially while first learning stone-tool making?

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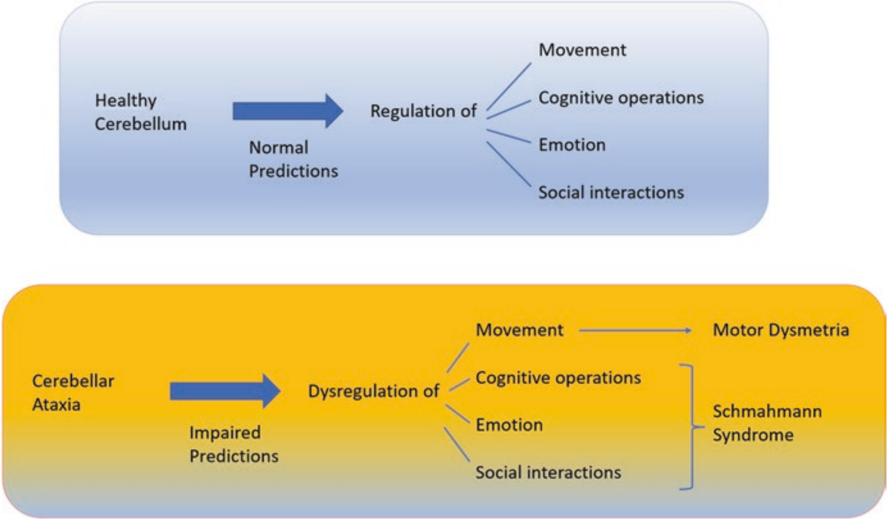
Chapter 6
Cerebellar Disorders: At the Frontiers of Neurology, Psychiatry, and the Modern Approach to Psychology

Manto Mario



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M. Manto et al., *The New Revolution in Psychology and the Neurosciences*,
https://doi.org/10.1007/978-3-031-06093-9_6

Abstract Cerebellum contributes to numerous motor and non-motor functions, optimizing motor skills and contributing to a wide array of behaviors. This is not surprising if one considers that the cerebellum contains about 60% of the brain neuronal population and on the basis of the topographically organized communication in multiple segregated cerebello-cerebral loops running in parallel between the cerebral cortex, brainstem, cerebellum, and thalamic nuclei. It is also now established that cerebellum communicates directly with the basal ganglia through disynaptic connections. Cerebellum plays a critical role in forward models allowing anticipation. Indeed, cerebellar machinery is a critical CNS structure to perform motor predictions related to body dynamics and to environmental changes. These predictions not only apply to motor acts but are also involved in cognitive/affective/social operations and are likely a substrate in the rise of *Homo sapiens* as underlined by Vandervert. Cerebellar cortex shapes cerebellar nuclei discharges by a mechanism of inhibition/disinhibition and interacts closely with the inferior olive through multiple olivo-cortico-nuclear modules. After two centuries of clinical observations showing a considerable variability in the semiological expression of cerebellar disorders, the field of clinical ataxiology is now based upon three groups of cerebellar symptoms gathered in a cerebellar motor syndrome (CMS), a vestibulocerebellar syndrome (VCS), and the Schmahmann's syndrome (SS/CCAS: cerebellar cognitive affective syndrome). All these clinical deficits can be grasped as the consequences of impaired predictions leading to a common denominator: dysmetria. Thanks to the numerous forms of plasticity and its anatomical property of redundancy, the cerebellum is highly reconfigurable. This feature should be exploited to reduce the neuropsychological, neurological, and psychiatric burden of cerebellar disorders, both for prevention and therapeutic approaches.

Scheme of the Consequences of a Cerebellar Lesion Upon Motor, Cognition, Emotion, and Social Interactions

Must-Read Quick Overview for All Students

Cerebellar circuitry has attracted researchers for many centuries. The geometrical arrangement of cerebellum is unique, made of a repetitive configuration. It was originally supposed that the cerebellum is a pure motor coordinator, but it is now established that its roles extend to cognitive operations, linguistic skills, affective regulation, and social interactions. This has huge impacts for the daily management of all the disorders affecting the cerebellum. Brain can be compared to your bank account in terms of number of neurons. The cerebellum would represent the majority of the money in this account. You understand why the research interest in the understanding of cerebellar circuitry has grown exponentially. In this chapter, you will follow the history of cerebellar research and the milestones achieved during 250 years of research. You will learn how the cerebellar circuitry is connected with cerebral cortex, how the semiology is currently applied in the clinic, and the importance of a multidisciplinary approach. Once you have put a foot in the understanding of the secrets of cerebellar circuitry, you will understand why cerebellar researchers are fascinated by this part of the brain.

History of the Cerebellum and Cerebellar Disorders

The cerebellum has been a subject of interest for centuries. It was initially suggested that it conveyed strength to motor nerves (Galen) and was a center of memory (Albertus Magnus) or a center controlling cardiovascular activities (Thomas Willis) (Schmahmann, 2016a, b). In the early 1800s, Gall, the creator of phrenology, argued that cerebellum was the area of self-preservation of the species (Gall & Spurzheim, 1809).

Vicq d'Azyr (1786) depicted the gross anatomy of the cerebellum, and Malacarne (1776) was the first to provide a detailed description of the human cerebellum. He described cerebellar foliation and used the terms vermis, lingula, pyramid, and tonsils, which are used nowadays. Malacarne suggested that the number of cerebellar folia was influenced by the environment, providing the first step in our current understanding of neuroplasticity (Zanatta et al., 2018). He quantified the number of cerebellar folia to about 600 laminae. He presumed that cerebellum was related to intelligence.

Historically, the studies of Rolando (1809) were decisive since they demonstrated a link between cerebellum and motor control. Rolando performed ablation of the cerebellum in animals and observed abnormal posture and erratic movements. Rolando was aware of the experiments of Galvani (1780s) on "animal electricity" (Galvani thought of a fluid secreted by the brain) and Volta (1799: a battery based on pairing of silver and zinc plates separated by brine-soaked paper disks). For Rolando, a part of the brain should work as a battery and should be constituted of overlapping disks (Coco & Perciavalle, 2015). The cerebellum seemed the right structure given its characteristic overlapping laminae. Rolando presumed that, if the cerebellum is the battery that produces electricity for muscle activity, its removal would produce paralysis: "Qual maggior prova per dimostrare, che dal suddetto viscere si separa un fluido analogo a quello, che dallo strumento citato si sviluppa? Qual più retta conseguenza, se esportato guasto o distrutto il cervelletto cessa ogni influsso del fluido nerveo nei muscoli destinati alla locomozione?" (What most evidence to prove that the said organ generates a fluid similar to that which develops from the mentioned device? What most direct consequence if removed, destroyed, or spoiled the cerebellum ceases any influence of the nervous fluid on the muscles for locomotion?) (Coco & Perciavalle, 2015). Rolando removed the cerebellum in a young goat and observed that the animal could no longer stand up "non altrimenti che se fosse paralitico" (not otherwise than if it was paralyzed). Rolando made thus for the first time the link cerebellum-electricity-motor activity. Fodera (1823) assessed in particular the effects of cerebellar lesions in pigeons and guinea pigs. He confirmed the role of the cerebellum in the control of postural tone. Flourens (1824) was probably the first scientist underlining that the cerebellum was critical for coordination of movements: “dans le cervelet réside une propriété dont rien ne donnait encore l’idée en physiologie, et qui consiste a ordonner ou coordonner le mouvements voulus par certaines parties du système nerveux, excités par d’autres” (in the cerebellum lies a property which nothing still gave the idea in physiology, that is to put in order or to coordinate movements wanted by certain parts of the nervous system, excited by others) (Flourens, 1824). At the same period, Magendie pointed out that a key function of the cerebellum is the control of equilibrium. In 1891, Luciani (1891) formulated a set of cerebellar symptoms: atonia, asthenia, astasia (the three symptoms forming Luciani’s triad), and added later dysmetria (Manni & Petrosini, 1997). He stressed the role of the cerebellum in regulation of postural tone and muscle strength. He denied wrongly the contribution of the cerebellum in coordination.

In terms of cellular organization, Purkyné (1837) reported the Purkinje neuron and at the beginning of the twentieth century, and both Golgi and Cajal reported the first detailed report of the cellular organization of the cerebellar cortex. Mossy fibers, glomeruli, climbing fibers, and parallel fibers were reported, establishing the fundamentals of cerebellar microcircuitry.

At the beginning of the twentieth century, Holmes provide detailed reports of the consequences of cerebellar injuries on clinical deficits. In particular, he examined injured soldiers during the first World War. The injuries to the occipital region and the cerebellum were common due to poorly designed helmets (Haines, 2016). He insisted on the motor consequences of a lateral cerebellar lesion, with a disruption of movements ipsilaterally. He noted that lesions restricted to the cerebellar cortex tended to recover more quickly than lesions involving cerebellar nuclei. He also found that hypotonia could be observed in large cerebellar injuries. Holmes pointed out the importance of dysmetria (movements wrongly proportioned) and subdivided this core symptom into hypermetria (excessive movement) and hypometria (premature arrest). He provided a detailed observation of the rebound phenomenon (failure of the antagonist muscles to stop the limb) and diadochokinesia (alternate movements). He also reported on intention tremor. Babinski described asynergia and was probably the first to report on diadochokinesia, before Holmes.

Studies of Jansen and Brodal led to the subdivision of the cerebellum into a medial zone (vermis/fastigial nucleus: control of posture and gait), an intermediate zone (paravermal cortex/nucleus interpositus: control of skilled movements of the ipsilateral limb), and a lateral zone (hemispheral cortex/dentate nucleus: control of skilled and fast movements of the ipsilateral limb). Larsell’s work has led to a coherent terminology of lobes and lobules (I–X), which is widely used today (Haines, 2016). With the identification of the primary fissure and the posterolateral fissure, he delineated the anterior lobe (lobules I–V) from the posterior lobe (lobules VI–IX) and the posterior lobe from the flocculo-nodular lobe (lobule X). Crus I and Crus II correspond to the superior and inferior semilunar lobules, respectively. Larsell emphasized the mediolateral continuity of the lobules of the vermis and hemispheres (Voogd & Marani, 2016). Voogd (1964, 1969) demonstrated that the cerebellum is organized into parasagittal zones (vermis, zones A and B; paravermis, zones C1–C3; hemispheres, zones D1 and D2). While the lobules are formed by the structural foliation of the cerebellar cortex, stripes are formed by the longitudinal distribution pattern of Purkinje cell subsets of given molecular expression profiles (Sugihara, 2021). Indeed, Purkinje neurons are heterogeneous in terms of molecular expression, as shown by the striped distribution of aldolase C (zebrin II). Stripes arise from a reorganization of embryonic Purkinje cell clusters, with both afferent (climbing fiber axons, mossy fiber axons) and efferent (Purkinje cells) axonal projection patterns being tightly correlated to the organization in both lobules and stripes in the cerebellar cortex (Sugihara, 2021). In other words, lobules and stripes frame the topography of axonal projections.

In the 1960s, Eccles reported the precise neuronal connectivity in the cerebellar cortex and Ito discovered that the projection from Purkinje neurons to cerebellar nuclei was inhibitory. Climbing fibers were found to provide a very powerful excitatory synaptic input to Purkinje neurons, resulting in action potentials known as complex spikes, whereas simple spikes (which can be considered as regular action potentials) are generated intrinsically and following mossy fiber-parallel fiber inputs.

In the years 1940s and 1950s, autonomic hypothalamic outburst and rage-like behavior following electric stimulation of the cerebellum. Prescott (1970) suggested that the cerebellum is involved in emotion. Heath investigated the influence of the cerebellum on the activity of the septal region, hippocampus, and amygdala of cats and rats (Heath et al., 1978). Stimulation of the vermis, fastigial nucleus, and midline folia of the cerebellum facilitated units in the septal region and inhibited the hippocampus, potentially suggesting specific types of cerebellar simulation in the treatment behavioral disorders and epilepsy.

Around 1970, Marr (1969), Ito (1970), and Albus (1971) have conceptualized the computational principle of the cerebellum, referred as the Marr-Albus-Ito model (Yamazaki, 2021). The hypothesis is based on two major assumptions:

- Mossy fibers project to granule cells which encode the signals and distribute processed messages to Purkinje neurons.
- Climbing fibers adjust the strength of granule cells-Purkinje neurons synapses (see also plasticity below).

According to this model, the inferior olive is the source of error signals conveyed by the climbing fibers in order to drive learning mechanisms.

The current leading theory is the theory of internal models. Because of the inevitable delay in reaching the brain, the sensory feedback information cannot be processed online: the brain always observes the past state of the body (Tanaka et al., 2021). By a simulation of the skeletomuscular physics (internal model), the brain can control movements without relying on the peripheral feedback (Wolpert et al., 1998). Numerous psychophysical findings support the hypothesis that the CNS uses internal models (Ebner, 2013). A typical example is the change in grip forces anticipation during manipulations of object load with slippage. Compensatory actions occur without delay, implying an absence of sensory feedback from the hand for an immediate adaptation. The CNS acquires internal models predicting the trajectory of the hand. Another example showing that the CNS adapt and retains novel motor patterns is the adaptation of reaching movements to environmental changes in a force field and the subsequent aftereffects in absence of exposure to the field (Shadmehr & Mussa-Ivaldi, 1994).

The concept of internal model can be applied to cognition, affective behavior, and social interactions (Koziol et al., 2014; Ito, 2008). Cerebellum might encode internal models reproducing the essential properties of mental representations in the cerebral cortex (Ito, 2008). This would represent a mechanism by which intuition and implicit thought might function (see this volume). Both forward and inverse internal models of thought would be embedded in the cerebellum (Ebner, 2013). The forward model would represent the control of mental models/representations performed by the prefrontal cortex. The cerebellar machinery would generate the signals needed to manipulate an object. The implementation of a mechanism allowing predictions has likely played a prominent role in the evolution of culture, language, and stone-tools use, which are at the essence of *Homo sapiens* behavior (Vandervert, 2018).

Topography of Cerebellar Inflow/Outflow Tracts and Modern Imaging

Cerebellum is highly connected with the spinal cord, vestibular system, brainstem, basal ganglia, and cerebral cortex. Multiple pathways convey information from the body to the cerebellum (Ruigrok, 2016). Spinal pathways can be subdivided into (a) systems that will end as mossy fibers and (b) systems that reach the cerebellum via the inferior olive and will end as climbing fibers (Ruigrok, 2016). Spinocerebellar tracts target the anterior lobe of the cerebellum and lobule VIII (Oscarsson, 1965), which correspond to the sensorimotor cerebellum; Snider and Stowell (1944) had initially observed in animal responses in discrete regions of the cerebellar cortex, which were organized as follows: one map in the anterior lobe and two maps in the posterior lobe of the cerebellum (somatotopic organization with homunculi). The majority of neurons in inferior olive do not receive spinal projections and target the posterior lobe of the cerebellum. Cerebellar output toward the spinal cord is mediated by several routes, including the corticospinal, rubrospinal, tectospinal, vestibulospinal, and reticulospinal tracts (Ruigrok, 2016).

In addition to the pathways linking the cerebellum with the spinal cord, the cerebellum has also massive reciprocal connections with the cerebral cortex and subcortical structures, being part of multiple segregated loops running in parallel (Schmahmann, 2016a, b). The cerebrocerebellar projections are mediated in particular by the corticopontine and pontocerebellar tracts. Corticopontine projections arise from pyramidal neurons of layer V, especially Brodmann areas 4 and 6 according to studies in monkey (Glickstein et al., 1985). Projections from motor cortices and from the sensory cortex terminate preferentially in the caudal half of the pons.

Furthermore, the pons receives numerous projections from cerebral association areas (Schmahmann, 2016a, b):

- Prefrontal areas arising from dorsolateral and dorsomedial prefrontal cortices. Areas 8 (conjugate eye movements), 9/46 (spatial memory, working memory), 10 (planning and judgment), 9/32 (decision-making), and 44/45 (language) contribute also.
- Posterior parietal areas.
- Temporal lobe areas: superior temporal sulcus, superior temporal gyrus.
- Parastriate cortices and posterior parahippocampal gyrus.
- Cingulate areas.
- Anterior insular cortex.

The caudal pons is preferentially linked with the anterior lobe of the cerebellum, whereas the rostral pons is linked with the posterior lobe of the cerebellum. In other words, the anterior lobe (especially lobules IV–V) and lobule VIII (paramedian) receive afferents from pericentral motor and sensory cortices, and the posterior lobe (Crus I/II) receives afferents from cerebral association areas (Schmahmann, 2016a, b).

The cerebello-thalamo-cortical pathway (feedback limb) is arranged in a topographically precise manner. Cerebral association areas projecting to the cerebellum via the pons receive projections back via the thalamus, as showed by viral retrograde transneuronal transport experiments (Middleton & Strick, 1994). Cerebellar cortex projects to cerebellar nuclei with a mediolateral distribution. The anterior lobe and the dorsal dentate nucleus are linked with primary motor/premotor cortex, while the posterior lobe and ventral dentate nucleus are linked with prefrontal and posterior parietal regions (Dum & Strick, 2003). Thus, the dentate nucleus contains anatomically and functionally distinct motor and nonmotor domains. Cerebellar projections from cerebellar nuclei are directed to motor thalamic nuclei (VPLo, VL, nucleus X), ventral anterior nucleus, intralaminar nuclei, and medial dorsal nucleus.

In addition to the corticopontine projections, the inferior olive receives also indirect input from motor and associative regions of the cerebral cortex via the zona incerta and red nucleus (Schmahmann, 2016a, b). These signals will be conveyed to the cerebellar nuclei/cerebellar cortex through climbing fibers. The inferior olive is thus enrolled in loops linking cerebral cortex and brainstem nuclei with the cerebellum.

It is currently considered that cerebellum is composed anatomically of multiple modules. These correspond to a conglomerate of nonadjacent parasagittal bands of Purkinje neurons projecting to specific area of the cerebellar nuclei and gating segregated projections from the inferior olive; modules include assemblies of Purkinje neurons coherently active during some specific operations (D'Angelo & Casali, 2013). This modular organization subserves the multitude of activities of daily life.

Cerebellum is also connected reciprocally with the basal ganglia, the hypothalamus, and the limbic system (Schmahmann, 2016a, b; Maiti & Snider, 1975). The subthalamic nucleus projects to both motor and non-motor regions of the cerebellar cortex via the pons in a disynaptic projection, and dentate nucleus projects back in a disynaptic path to the striatum via the thalamus (Bostan et al., 2010). There is now a consensus for a dynamic interplay between cerebral cortex and the two major subcortical structures: the cerebellum and basal ganglia likely interact directly, and both of them are linked to the cerebral cortex (Caligiore et al., 2017). An integrated network has emerged: the motor, cognitive and affective territories of each node are interconnected and might explain how abnormal activity at one node can have network-wide effects in neurological and psychiatric disorders (Bostan & Strick, 2018). Regarding hypothalamic nuclei, they project to the caudal third of pontine nuclei and also diffusely in the cerebellum (Aas & Brodal, 1988). Dentate nuclei project back to the contralateral hypothalamus. The mamillary bodies project to pontine nuclei and also directly to the anterior and posterior lobe of the cerebellum. A mamillo-pontocerebellar pathway has been demonstrated in cats, likely mediating learning and motivational processes (Aas & Brodal, 1989). Hippocampus, septal nuclei, and amygdala are also interconnected with the cerebellum. Overall, all these anatomical nodes form a complex network which allow the cerebellum to modulate parameters of movement, cognitive and affective processes, emotion, and autonomic control (Schmahmann, 2016a, b).

The advent of the 3D MRI atlas of the cerebellum has greatly facilitated the understanding of the contribution of the cerebellum in numerous sensorimotor tasks, updating Larsell's nomenclature toward a clinical use and allowing scientific applications of functional imaging (Schmahmann et al., 2000). The topography of the areas of the cerebellum involved in motor control, cognitive tasks, social tasks, and emotion is much better understood now (Stoodley et al., 2012). The cerebellum can be divided into areas depending on connectivity with sensorimotor versus multimodal association cortices. Finger-tapping activates ipsilateral cerebellar lobules IV–V and VIII, in agreement with descriptions of the cerebellar homunculi. Verb generation activates right cerebellar lobules VI–Crus I and a second cluster in lobules VIIB–VIIIA. Working memory tasks, which are essential for daily activities by holding finite amount of information in mind until no longer required, activate bilateral regions of lobules VI–VII (Marvel et al., 2019; see also this volume). Overall, overt movement activates sensorimotor cortices along with contralateral cerebellar lobules IV–V and VIII, whereas more cognitively demanding tasks activate prefrontal and parietal cortices along with cerebellar lobules VI and VII (Stoodley et al., 2012). Resting state connectivity studies and diffusion tension imaging (DTI)-based tractography have pushed our understanding of cerebellar networks one step further. However, DTI-based tractography still faces challenges in terms of spatial resolution, which prevents a full mapping of the corticopontocerebellar fibers (van Dun et al., 2016). The independent component analysis-based functional connectivity has demonstrated the following parallel cerebro-cerebello-cortical networks (Habas, 2016):

- The sensorimotor network: motor and premotor cortex, lobules V–VI and VIII.
- The right and left executive networks: dorsolateral prefrontal cortex, parietal cortex, and Crus I/II.

- The limbic salience network: frontal and insular cortices, lobules VI/VII. This network is implicated in interoception, emotions, and autonomic regulation.
- The default-mode network: dorsomedian prefrontal cortex, posterior cingulate cortex, retrosplenial and parahippocampal cortices, precuneus, and lobules VII and IX. This network is involved in consciousness, self-agency, memory, and mental imagery.

Plasticity of the Cerebellum and Cerebellar Reserve

At a cellular level, several forms of plasticity have been demonstrated in the cerebellar circuitry, a key feature underlying the learning properties and the reconfiguration potentialities of the cerebellar machinery. The concomitant low-frequency stimulation of parallel fibers and climbing fiber inputs induces an attenuation of the parallel fiber-Purkinje neuron synapse, called long-term depression or LTD (Ito et al., 1982). This plasticity is mediated in particular by glutamate receptors (mGluR, AMPA-R) and a rise of intracellular calcium. In addition, the parallel fiber-Purkinje neuron synapse is also the site of long-term potentiation (LTP), which is stimulus frequency-dependent. Plasticity occurs also at the level of GABAergic synapses such as the interneuron-Purkinje cell synaptic LTP (Hausser & Clark, 1997). Plasticity is also observed at the level of the mossy fiber-granule cell synapse and cerebellar nuclei (Shen, 2016).

The rich repertoire of plasticity mechanisms makes of the cerebellum a unique machinery contributing to the cerebellar reserve. The various cerebellar ataxias (CAs) encountered in clinical practice result from various lesions both in terms of location and mechanisms and present clinically with motor, oculomotor, and cognitive/affective/social deficits. Surprisingly, cerebellar deficits may recover remarkably, as pointed out by Holmes in 1917 (Mitoma & Manto, 2021). Cerebellar reserve is defined as the capacity for compensation and restoration consecutively to pathological lesions in the cerebellar circuitry. Both the enrichment in numerous forms of plasticity and the redundancy of cerebellar inputs are key features of cerebellar reserve (Mitoma et al., 2021). Mossy fibers conveying peripheral and central information run mediolaterally over a wide area of the cerebellum, resulting in the innervation of multiple adjacent microzones. Thus, a single microzone receives redundant information, a property that can be used in pathological conditions.

Cerebellar reserve contains two components: a structural aspect and a functional aspect. The *structural cerebellar reserve* refers to a compensation of a structural lesion in a given area of the cerebellum (for instance, in case of a cerebellar stroke, traumatic injury, local tumor, or abscess) by an unaffected area of the cerebellum: cerebellar structures located around the lesion or contralateral cerebellar hemisphere. The degree of reversibility of symptoms is assumed to depend on the extension of the lesion. Moreover, reversibility might be determined by the proximity of the area lesioned with the substitution area (Mitoma et al., 2020). If the backup structure is near the lesion, the capacity to restore the function might be decreased (high-risk cerebellar reserve). The *functional cerebellar reserv*e designates a compensatory mechanism or a restoration process, which takes place within the lesion site as a result of a functional reorganization. This occurs for instance in case of degenerative ataxia, immune ataxias, or metabolic ataxias. It is well-known that intensive rehabilitation may promote functional restoration in degenerative disorders such as spinocerebellar ataxias. It is remarkable to note that motor recovery may be considerable in case of extensive cerebellar lesions, as shown for instance by the experimental model of hemicerebellectomy (Federico et al., 2006). However, a second lesion may trigger a decompensation. This has been reported experimentally for a subsequent lesion at the level of the sensory cortex (Mackel, 1987). Indeed, if the sensory cortex is removed secondarily to an initial cerebellar lesion and after a phase of recovery, the motor performance is much worse again. In addition, removal of the sensory cortex ahead of the cerebellar damage increases the cerebellar deficits and severely impacts on the recovery process, which follows a cerebellar damage. Extra-cerebellar structures participate in the relearning of lost cerebellar functions. Evidence of an interplay between the cerebellum and the sensory cortex exists also in human. Patients with a cerebellar stroke may fully recover and subsequently show a cerebellar decompensation caused by a stroke at the level of the posterior parietal association area (Manto et al., 1999).

The concept of cerebellar reserve is particularly relevant for neuropsychological, neurological, and psychiatric evaluation of cerebellar patients. It is now possible to assess the cerebellar reserve, thanks to psychometric tools, neuropsychological assessments, and advance imaging techniques. This is particularly pertinent for the follow-up of patients and from a therapeutic perspective (Mitoma & Manto, 2021). The development of novel tools based on the quantification of predictive mechanisms is promising (Mitoma et al., 2020).

The Three Cerebellar Syndromes

The current clinical view of cerebellar deficits considers that cerebellar symptoms can be gathered into three groups of symptoms:

- A cerebellar motor syndrome (CMS).
- A vestibulocerebellar syndrome (VCS).
- Schmahmann syndrome/cerebellar cognitive affective syndrome (SS/CCAS) (Cabaraux et al., 2021).

The common denominator of cerebellar deficits is dysmetria, encompassing both motor dysmetria and dysmetria of thought. Dysmetria is also observed in CAs in the domains of affective regulation and social behavior.

Cerebellar Motor Syndrome (CMS)

The cerebellar motor syndrome is typically observed in patients presenting lesions of the anterior lobe (lobules I–V). Patients with lesions of the lobules VI–X show relatively minor motor symptoms. There is a somatotopic correlation, which can be summarized as follows:

- Lesions of the vermal/paravermal lobules III–VI are correlated with ataxia of lower limbs.
- Lesions of vermal/paravermal/hemispheral lobules IV–VI are correlated with upper limb ataxia.
- Lesions of paravermal/hemispheric lobules V–VI are correlated with dysarthria.
- Lesions of the superior vermis (lobules II, III, IV) are correlated with ataxia of posture/gait (Schoch et al., 2006).

Regarding cerebellar nuclei, lesions of fastigial nuclei cause ataxia of stance/gait, lesions of the interposed nuclei/adjacent dentate nuclei are associated with limb ataxia, and lesions of the dentate nuclei trigger dysarthria/limbs ataxia. The typical presentation of stroke in the superior cerebellar artery (SCA) territory includes ipsilateral motor dysmetria, dysarthria, and gait ataxia/lateropulsion, usually in the absence of cognitive/affective deficits or in association with subtle cognitive dysmetria.

Vestibulocerebellar Syndrome (VCS)

Oculomotor deficits are often manifest in CAs. Patients exhibit various combinations of dysmetria of saccades, saccadic pursuit, impaired vestibulo-ocular reflex (VOR), deficits in fixation, and errors in vergence. Causal lesions are found at the level of the vermis and/or the flocculo-nodular lobe.

Schmahmann Syndrome/Cerebellar Cognitive Affective Syndrome (SS/CCAS)

Lesions of the posterior lobe are associated with a constellation of deficits in the executive functions, in visuospatial performances, in linguistic processing, and in regulation of affect (Schmahmann & Sherman, 1998). This is detectable during the assessment of working memory, ideational set shifting, perseverations, drawings, verbal fluency, and prosodia. Visuospatial sequences are particularly distorted, including for the conceptualization of figures. Patients with lesions in the territory of the posterior inferior cerebellar artery (PICA) or with vermian lesions often exhibit a flattening of affect, disinhibition, and impulsivity and often make inappropriate comments. The general consequence is a lowering of intellectual functions, especially in case of bilateral and acute lesions. The spectrum of clinical deficits corresponds to a genuine link between neuropsychology, neurology, and psychiatry (Schmahmann et al., 2007). Following the report/identification of Schmahmann syndrome, the syndrome has been reported in a majority of cerebellar disorders, encountered in the clinic from sporadic ataxias to hereditary disorders, and is still likely overlooked in many patients (Argyropoulos et al., 2020).

The posterior fossa syndrome is an example of a severe Schmahmann syndrome occurring mainly in children after posterior fossa tumor surgery, even if cases may occur following trauma, infection, or stroke. Patients show a transient mutism associated with a combination of neuropsychological, neurolinguistic, and neurological motor symptoms. Daly and Love provided the first description in 1958 in a 14-year-old posterior fossa tumor patient who exhibited a clinical syndrome encompassing "akinetic mutism", cognitive, affective, and neurological deficits (Daly & Love, 1958). Rekate and colleagues were the first to point out a "muteness of cerebellar origin," now recognized as cerebellar mutism (Rekate et al., 1985). The authors reported a temporary loss of speech in six children with an acute bilateral damage to large areas of both cerebellar hemispheres, including the dentate nuclei. Muteness lasted 1–3 months. All patients were severely dysarthric during recovery. The sequence of events is the following: transient mutism occurs with a delayed onset of 0–15 days (mean of 2 days) and has a limited duration extending from 1 day to 2.5 years (mean of 43 days). Mutism is followed by dysarthria, hence the terminology of mutism and subsequent dysarthria. Preoperative symptoms often include various degrees of inattention, depression, irritability, impaired verbal fluency, slowed speech, motor ataxia, headache, and vomiting. The range of postoperative symptoms is wide (Marien & Manto, 2016). In particular, patients show irritability, apathy, stereotypies, bizarre behavior, and autistic traits. Obviously, there are strong similarities between Schmahmann syndrome reported in adults and the posterior fossa syndrome observed in children. The executive, visuospatial, affective, and linguistic domains are affected in both cases. Risk factors to develop the posterior fossa syndrome include the midline location of the tumor, brainstem extension, and tumor type. Cerebellar mutism is presumed to result from damage to dentate nuclei and/or the dentato-thalamo-cortical pathways. Midline tumors infiltrate local tissues and cause edema. The delayed onset of symptoms after surgery might be related to ischemia consecutively to surgical manipulation, vasospasm (vasospasm is a well-known complication of subarachnoid hemorrhage and typically starts from 3 days to 14 days after the bleeding), and diaschisis. Traction may cause axonal injuries or axonal distortions in white matter bundles as supported by MRI/DTI studies, and pons compression has been observed in several cases (Morris et al., 2009; McMillan et al., 2009). The resolution of symptoms might be related to a normalization of cerebellar blood flow (Marien & Manto, 2016). Recovery is rarely complete. Sequelae include motor ataxia, nystagmus, dysarthria, attentional problems, impaired verbal comprehension, affective symptoms, behavioral deficits, and cognitive dysfunction. Overall, patients are more likely to present obsessive-compulsive behavior, social difficulties, anxiety, and depression. The mean IQ tends to be lower and academic achievement is often poor. Special education may be needed.

Social interactions are highly complex and are also under cerebellar control. CAs may exhibit an autistic-like aspect. Autism is a neurodevelopmental disorder characterized by impaired social interactions, difficulties of communication, and repetitive/stereotyped behaviors. The cerebellum is one of the sites of neurobiological changes in autism. Genetic studies and neuroimaging investigations point toward a key role of the cerebellum. Postmortem studies have demonstrated a reduction in the population of Purkinje neurons, especially in the posterior inferior portions (Bauman & Kemper, 2005). The posterior vermis contributes to behavioral regulation including mental flexibility (Schmahmann et al., 2007). Most animal models of autism show cerebellar abnormalities (Ellegood & Crawley, 2015). Strikingly, preterm infants with isolated cerebellar damage are 40 times more likely to be diagnosed with autism (Limperopoulos et al., 2007). The cerebellum modulates also the reward circuitry, which contributes to social behavior (Carta et al., 2019). The cerebellum sends direct excitatory projections to the ventral tegmental area (VTA), suggesting that cerebellar circuitry is an—so far unsuspected—actor of reward mechanisms. A larger striatum, a smaller cerebellum, and a smaller amygdala are all consistently found in autistic patients. In the limbic system, the hippocampus, amygdala, and entorhinal cortex show small cell size and increased cell packing density at all ages, indicating a pattern consistent with development curtailment. It is now established that lesions of the limbic cerebellum (vermis/fastigial nucleus) are associated with dysregulation of affect (Schmahmann et al., 2007). Premature infants with isolated cerebellar hemorrhagic injury show significantly lower mean scores in motor disabilities, expressive language, delayed receptive language, and cognitive deficits (Limperopoulos et al., 2007). Isolated cerebellar hemorrhagic injury is significantly associated with severe functional limitations in daily activities. Typically, children with congenital lesions including cerebellar agenesis, dysplasia, and hypoplasia exhibit a set of symptoms, which can be interpreted as dysmetric behavior: distractibility, hyperactivity, impulsiveness, disinhibition, anxiety, ritualistic and stereotypical behaviors, illogical thought, lack of empathy, ruminative and obsessive behaviors, dysphoria and depression, tactile defensiveness and sensory overload, apathy, childlike behavior, and inability to appreciate social boundaries (Schmahmann et al., 2007). Both structural and functional connectivity between the cerebellum and cerebral cortical nodes are disrupted (Olivito et al., 2018). Functional connectivity is impaired between (a) right posterior cerebellum and cerebral cortical nodes of language, (b) left dentate nucleus and cerebral cortical nodes of the default mode network, and (c) bilateral Crus I and medial regions of the mentalizing network (Olivito et al., 2017; Van Overwalle et al., 2014). According to the theory of internal models, cerebellar circuitry would allow the anticipation of other person's behavior, detect violations in social interactions, and activate corrections/adaptations in the internal models. Overall, dysmetria of thought and behavior assembles several major psychological domains symptoms: disorders of attention, impaired emotional regulation, social skill set/autism spectrum disorders, and psychosis spectrum disorders (Schmahmann et al., 2007).

Conclusion and Future Directions

As discussed in the chapters of this volume, cerebellar research is at the frontiers of neurology, psychiatry, and the modern approach to psychology. Our view of cerebellar functions is considerably broader than expected. The traditional consideration of the cerebellum as a pure coordinating tool has changed drastically, thanks to detailed neuroanatomical investigations, functional neuroimaging studies, and in-depth neuropsychological assessment of cerebellar patients (Marien & Manto, 2016). This is not surprising given the huge number of neurons in the cerebellar circuitry and its vast network of communications with cerebral cortex, limbic system, basal ganglia, brainstem nuclei, and spinal cord. No other structure in the CNS is better suited than the cerebellum to modulate motor, cognitive, linguistic, affective, and social activities. This is in perfect line with the clinical observations of deficits observed in cerebellar patients. The cerebellum is endowed with the capacity of restoring functional synapses, a unique feature which should be used in the assessment and management of cerebellar disorders. The visionary hypothesis of Malacarne on the impact of environment on cerebellum fits with the cerebellar research performed during more than two centuries. Abnormal functioning in segregated loops between cerebellum and extra-cerebellar hubs contributes to the pathogenesis of major brain pathologies at the frontiers of neuropsychology, neurology, and psychiatry including autism, schizophrenia, and depression. Preventive strategies and therapies tailored to the needs of each patient are needed. Physical, occupational, and cognitive rehabilitation of cerebellar patients should be further improved in individualized approaches, taking into account the various aspects of cerebellar reserve: motor, oculomotor, cognitive, affective, and social. At the level of neuropsychological interventions, neurocognitive rehabilitation should focus on interrelated aspects: attention, executive functions, memory, visuospatial capacities, and verbal communication. The detrimental consequences of the three clinical cerebellar syndromes require a multidisciplinary team, where expertise in neuropsychology, neurology, and psychiatry is mandatory to achieve progress. Therapies will go along with longitudinal studies dedicated to motor, cognitive, affective, and social issues encountered by cerebellar patients. The scientific community can now take advantage of the integration of clinical data, neuropsychological assessments, biological evaluations (blood, CSF, other fluids), and advanced neuroimaging tools, both structural and functional.

Exercises

1. Imagine you are discussing with a friend. How would you explain with your own words Schmahmann syndrome/cerebellar cognitive affective syndrome?
2. Paul has been working in a post office for 20 years. He interacts with many people. He develops a cerebellar stroke and is diagnosed with severe cognitive dysmetria. What could be the impact during his daily work?
3. Return to the Jeremy Schmahmann quote that appears at the beginning of the Table of Contents of this book. In reading through this present chapter, what do you feel is Schmahmann's most interesting contribution to cerebellum research?

Declarations Funding
No specific funding to declare.

Conflict of Interests
The author declares no conflict of interest.

Ethical Committee Request
Not applicable.

Data Availability
The concept reported in this article is not based on raw data.

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https://doi.org/10.1007/978-3-031-06093-9