Vygotsky Meets Neuroscience
The Cerebellum and the Rise of Culture through Play

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The author suggests the brain's cerebellum and cerebral cortex are the origin of culture and considers the cerebellar models that came to constitute culture to be derived specifically from play. He summarizes recent research on the behavioral, cognitive, and affective evolution of the cerebellum and the cerebral cortex that shows the development of these processes created increased efficiencies, unconscious control of complex situations, the ability to predict probable future circumstances before they occur, error correction in emotional and social situations, and an unconscious blending of components to solve new problems. He argues that human play evolved from animal play, which helped train animals to deal with unexpected circumstances. As animal play evolved toward human play, rule-governed imagination allowed play to help predict events through sequence detection. Human play then led to the advent of culture, which socially amplified the advantages of these adaptations. The author contends that this creative blending of cerebellar models provides an explanation of Lev Vygotsky's (1978) most compelling insights about play. He concludes that, although play and culture appear dramatically different, they develop from the same brain mechanisms. **Key words**: animal play; brain evolution; cerebellum; creativity; culture; play; socialization; Vygotsky; zone of proximal development

Introduction

In the last million years, the human cerebellum, an unusually dense and furrowed structure tucked under the two brain hemispheres, has increased three- to fourfold in size, and in the evolutionary process it has gained massive connections with the highest cognitive functions in the cerebral cortex (Bostan, Dum, and Strick 2013; Imamizu et al. 2007; Leggio and Molinari 2015; Leiner, Leiner, and Dow 1986, 1989; Stoodley, Valera, and Schmahmann 2012; Strick, Dum, and Fiez 2009). I have recently argued that because the cerebellum builds

American Journal of Play, volume 9, number 2 © The Strong
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models from repetitive behavioral, cognitive, and affective processes; operates at an unconscious level; and creatively predicts and anticipates future circumstances, it—and not the cerebral cortex as traditionally thought—has played the prominent role in the origin, maintenance, and advancement of culture (Vandervert 2016a). I define culture in this article as the beliefs and activities learned through socialization and shared by the members of a particular group of people, with socialization being "the process of learning the meanings and practices that enable us to make sense of and behav[e] appropriately in that culture," (Sensoy and DiAngelo 2012, 15).

Purpose

In this article, I discuss the impact of the dramatic increase in the size of the cerebellum over the last million years that drove animal play and then human play toward the genesis of culture. Specifically, I follow Spinka, Newberry, and Bekoff (2001), who defined play as "training for the unexpected." Beginning from this perspective, I argue that animal play evolved toward human play as the cerebellum expanded its ability to adapt to the unexpected by predicting and anticipating future circumstances—and that animal play, human play, and culture serve the same general adaptive purposes. Given this, I contend that the insights, principles, and conclusions related specifically to play of Lev Vygotsky's *Mind in Society* (1978) are essentially correct and make strong intuitive sense because they derive from the evolutionary, cerebellum-driven origin of culture through play.

First, however, I think it helpful to offer a brief sketch of the new research concerning the behavioral, cognitive, and affective contributions (including creativity) of the cerebellum as it has evolved over the last million years.

The Other Four-Fifths of the Brain's Neurons and the Evolution of Play and Culture

In two watershed articles, Leiner, Leiner, and Dow (1986, 1989) pointed out that over the last million years the human cerebellum increased three- to fourfold in size and had, in the process, developed new neural projections (pathways) to the prefrontal and associated areas of the cerebral cortex. Based on this enormous increase and the new connections with the highest cognitive areas of the cerebral cortex, Leiner, Leiner, and Dow (1986) convincingly argued that the cerebellum had thereby evolved beyond its initial function of initiating motor activity to a surprisingly expanded role of "the skillful manipulation of ideas" (444). They further pointed out that the increase was accompanied by twenty million nerve tracks on each side of the brain going from the cerebral cortex (including from the limbic, parietal, and prefrontal areas for planning and language functions) to the cerebellum (Leiner, Leiner, and Dow 1986, 1989). By comparison each of the two optic nerves contain approximately one million nerve tracts running back to the visual areas of the brain. In addition to these forty million nerve tracts to the cerebellum, there is a bundle of nerve fibers in the cerebellum called the dentate nucleus that conveys a multitude of pathways to the cerebral cortex where planning, language, and emotional processing takes place (Leiner, Leiner, and Dow 1989). I argue that the expansion and differentiation of the dentate nucleus played a key role in the transition from animal play to human play and culture, and I return to the dentate nucleus and that transition in some detail.

Research shows that, through repetitive experience, the uniquely human cerebellum enhances the behavioral, cognitive, and affective functions of the cerebral cortex in at least five ways. First, the cerebellum increases the speed, efficiency, consistency and appropriateness of motor, cognitive, and affective processes by sending refined neural routines (models) to the cerebral cortex (Ito 1997, 2008, 2011; Leiner, Leiner, and Dow 1986, 1989; Schmahmann 1991, 2004, 2013). In the case of appropriateness, a normally operating cerebellum prevents, for example, personality changes that have been characterized as flattening or blunting of affect and disinhibited, or inappropriate behavior (Schmahmann 2004). Moreover, just as in musical training, when an emotion-driven player improvises but attempts to remain true to the nuances of feeling intended by the composer, so must the executive and affective processes closely monitor the general appropriateness of individual behavior. Such fluid, largely unconscious skills are prominently cerebellum driven.

Second, the cerebellum learns internal models that unconsciously control any and all movement, cognitive, and affective processes in preparation for both expected and unexpected circumstances—for example, playing the piano without sheet music, memorizing the multiplication tables, or practicing shooting basketballs into hoops. The unconscious situational awareness for which Navy SEALS train would not be possible without the cerebellum (Ito

1997, 2008, 2011; Leiner, Leiner, and Dow 1986, 1989; Schmahmann 2013).

Third, by encoding serial events and then quickly reconstructing the sequence, the cerebellum can alert the cerebral cortex to what will happen before it happens, thus predicting future sequential events and processing anticipatory measures (Akshoomoff, Courchesne, and Townsend 1997; Leggio and Molinari 2015). To do anything from type on a keyboard to play a musical instrument to engage in the game of chess, the brain learns sequences of attentional focus that anticipate what will be required next (Vandervert 2016b, 2016c). With practice, these sequences of attention become controlled by the cerebellum, largely unconsciously, which accelerates and optimizes the skilled performance.

Fourth, the cerebellum processes unlimited error correction through extended experience and practice, and that ability explains equally Albert Einstein's breakthrough visualization of travel alongside a beam of light and a child prodigy's stellar performance of Beethoven's *Für Elise*. Whether the mental process involves creativity in math or mastery of music, the cerebellum tracks all sequences to optimize results (Vandervert 2007, 2015, 2016b, 2016c; Vandervert, Schimpf, and Liu 2007).

And fifth, the cerebellum provides creative insights in both imagination and actual situations involving motor and mental processes. Such creative insights occur through the blending of cerebellar internals models (Imamizu and Kawato 2012; Imamizu et al. 2007; Yomogida et al. 2004). One example might again be Albert Einstein's outstanding creative achievements in science (Vandervert 2011, 2015; Vandervert, Schimpf, and Liu 2007).

Finally, note that Leiner, Leiner, and Dow's watershed speculations and hypotheses concerning the expansion from motor to both motor and 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, the particularly relevant ones include Akshoomoff, Courchesne, and Townsend (1997); Balsters et al. (2013); Ito (1997, 2008); Leggio and Molinari (2015); Liao et al. (2014); Marvel and Desmond (2010a, 2010b, 2012): Schmahmann (1997); Stoodley, Valera, and Schmahmann (2012); Strick, Dum, and Fiez (2009); and Vandervert (2013).

It is important to appreciate the sheer computational power that has developed over the last million years in the cerebellum relative to the cerebral cortex. Figure 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). We will describe precisely what these 69 billion neurons do and how they led from animal play to human play and to culture in a moment.

The Cerebellum's Dentate Nucleus: Ancestral Pathway to Play and Culture

Even though the dentate nucleus lies buried deep within the white matter of the cerebellum, it played a very important role in the evolution of language and the elaboration of culture over the last several hundred thousand years (Desmond and Marvel 2010a, 2010b; Vandervert 2016a). Cerebellum researchers Leiner, Leiner, and Dow (1986, 1989) and Vandervert (2011, 2016a) characterize this period as a "leap" forward because the cognitive functions of our *Homo erectus* ancestors increased and elaborated so dramatically in the transition toward modern humanity. Leiner, Leiner, and Dow (1986) pointed out that the dentate nucleus originally contained nerve tracts devoted only to motor functions. But in modern humans, the structure carries to the cerebral cortex both motor information (in an older dorsal motor loop) and cognitive information (in a newer ventral loop). The dorsal and ventral dentate nerve tracts work seamlessly together in, for example, silent inner speech and processes of imagination related to working memory (Marvel and Desmond 2010a, 2012). When you mentally rehearse a phone number as you look for your cell phone and then mentally retrieve that number to tap it in to the keypad, two portions of the dentate nucleus are deployed on the same task in working memory—first comes dorsal activation in the imagination of silent inner speech followed by ventral activation in the imagination of cognitive retrieval. This helps me describe how the evolution of the cerebellum's dentate nucleus provides a model that connects the origin of play in the cerebellum of animals to similar cerebellum-driven play in humans and how that human play led to the origin of culture.

The Play and Culture Adaptations of the Evolving Cerebellum

There are many scientific theories of animal play and many proposed components of animal play (Sharpe 2011). Here, we stay within a well-articulated

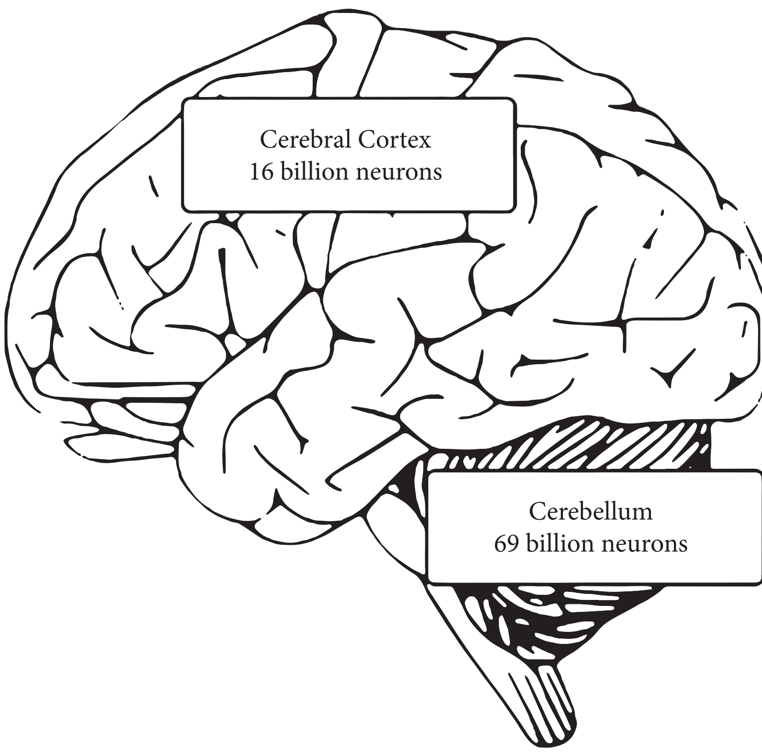

Figure 1. The figure illustrates relative positions of the cerebellum and the cerebral cortex along with recent approximations of the number of neurons in each. These approximations are from Lent et al. 2012.

concept of play that has been described in the context of its evolutionary adaptive advantages and can therefore be stated in terms of its likely neural evolution and neural mechanisms. Thus the definition of animal play I use follows in some detail the adaptive model proposed by Spinka, Newberry, and Bekoff (2001). These researchers referred to their model of play as "training for the unexpected."

> We hypothesize that a major ancestral function of play is to rehearse behavioral sequences in which animals lose full control over their locomotion, position, or sensory/spatial input and need to regain these faculties quickly. Animals learn how to improvise their behavior by chaining conventional

> movements *with* [italics added] atypical movements to get themselves back into a standard position. Sequences that link highly efficient species-typical motor patterns and standard body positions with atypical movements necessary for recovery from awkward positions often occur in biologically significant situations [notably, survival skirmishes].
>
> Besides the development of locomotor versatility in unanticipated situations, we hypothesize that animals in play learn how to deal with the emotional aspect of being surprised or temporarily disoriented or disabled. . . . In the presence of a predator, emotional overreaction leading to aimless panic [essentially losing their "cool"] will decrease an animal's chance of survival. . . .
>
> In short, we propose that play: (i) results in increased versatility of movements used to recover from sudden "gravitational," "kinematic," or "positional" shocks such as losing ground underfoot, falling over, being knocked over, being pinned down, or being shaken vigorously, and (ii) enhances the ability of animals to cope *emotionally with unexpected situations* [italics added]. These may include both "locomotor" shocks as described above, or "psychological" shocks such as suddenly being faced with frightening or dangerous stimuli, unexpectedly meeting a stranger, or experiencing sudden reversal of dominance. . . .
>
> If play has the function of training for the unexpected, then unforeseen situations [unforeseen to the young individual] should occur frequently in play. We suggest that animals actively seek and create unexpected situations in play. Specifically, we propose that mammalian play is a sequential *mixture* of (a) well-controlled vigorous locomotor movements similar to those used in "serious" behavior that load heavily on fitness traits such as escape from predators, intraspecific agonism, that is, within-species contests, or hunting fast or dangerous play; and (b) movements during which postural control is compromised, or the chance for random factors to influence movement is increased so that the animal is more likely knocked off balance, fall over, lose control of a play object, or fail to counter the actions of another animal. (143–44).

I quote this description of the adaptive value of play at length because both its repetition of behavioral, emotional, cognitive, and social components and its chaining (mixing) of these conventional and atypical locomotor components literally describe the key adaptive purposes of the evolution of the cerebellum (Ito 1997) and its five contributions to human development. The cerebellum is in fact the only part of the brain that through repeated experience (or practice), could orchestrate Spinka, Newberry, and Bekoff's "training for the unexpected" for use in the cerebral cortex. And, it appears to be the only part of the brain that uses highly repetitive play information like that described by Spinka et al.

that could provide a neural mechanism for unconscious socialization in animals and in human play and culture (Vandervert 2016a).

The Evolution of Animal Play to Human Play to Culture

Spinka, Newberry, and Bekoff (2001) also argued that the rapid alternation between conventional survival actions on the one hand and atypical, out of control actions on the other within the complex face-to-face play among animals of the same species required demanding cognitive and social activity—that is, socialization within the animal grouping. They suggested that play would have had great evolutionary selective advantage as animals evolved higher cognitive capacities. Play would have aided in socially identifying with conspecifics and may be related to the emotional richness necessary for having fun. Fun, in turn, is a powerful reinforcing motive for play. The combination of these cognitive, social, and emotional adaptive advantages would have constituted an evolutionarily adaptive positive feedback loop. (See, for example, Crespi [2004] for a detailed discussion of evolutionary positive feedback loops.) Winner (1996) provides a way to understand the operation of positive feedback loops directly in developmental and evolutionary contexts. She described gifted children as driven by positive feedback loops (although she did not specifically use the term) involving setting their own learning course, thus feeding back satisfaction, thus further setting their learning goals to higher levels, and so on. Winner further described these positive feedback loops as occurring within a combination of gifted children's drives toward "an insistence on marching to their own drummer" (where their advances in knowledge are exciting and motivating to them) and a "rage to master" (with intense and obsessive interest in their domain of precocity). It is no coincidence that positive feedback loops would govern the evolution of play toward culture and also be the drivers toward higher levels of intelligence. They are both adaptive outcomes of evolutionary survival and both involve the accelerated speed and appropriateness functions of the cerebellum (Vandervert 2007, 2016b, 2016c). As Winner (1996) points out in this regard, the child prodigy phenomenon is an extreme case of positive feedback on the high ability of a gifted child. I agree, and I have proposed that extreme performance development in a child prodigy is most importantly the result of accelerated cerebellar involvement in deliberate practice (Vandervert 2007, 2009a, 2009b).

Also in relation to the accelerated speed and appropriateness of the cognitive functions of the cerebellum, positive feedback loops aided the adaptations of the emerging cognitive functions in apes and prehuman Australopithecus. About one million years ago, the positive feedback loops associated with an explosive adaptive expansion of the cognitive functions of the cerebellum (Leiner, Leiner, and Dow 1986, 1989) likely helped play-driven socialization culminate in more complex and adaptive, language-driven socialization among *Homo sapiens* (Vandervert 2011) that began about eight hundred thousand years later. (Powell, Shennan, and Thomas 2009).

I am suggesting that human play derived from animal play, that a unity underlying the evolution of all mammalian play—their phylogeny—has favored play as training for the unexpected. This training provided a distinct benefit during that interval when the cerebellum evolved to foster the cognitive advances that aided social evolution toward humans. (See Spinka, Newberry, and Bekoff [2001] for more about this development.)

Play as the Main Driver of Culture and All Cultures as Shared Systems of Adult Play

I wish to polish up the play as "training for the unexpected hypothesis" a bit. First, I describe research on the mechanism by which the cerebellum learns to predict the unexpected during play and enculturation. Then, I describe the critical cerebellar mechanisms by which unconscious socialization and imagination become rule governed through repeated experiences in animal play, human play, and human enculturation. By doing so, I intend to demonstrate that, in all of these cases, the cerebellar mechanisms of socialization and imagination are the same.

The Cerebellum and the Unexpected during Play and Enculturation

As I have said, Leiner, Leiner, and Dow (1986, 1989) and Ito (1997, 2008, 2011) provided overwhelming evidence that the cerebellum specializes in the 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, Courchesne, and Townsend (1997) offered important detail about the cerebellum's building of a predictive and anticipatory unconscious structure into virtually all processes in the cerebral cortex.

> The cerebellum is a master computational system that adjusts responsiveness in a variety of networks to obtain a prescribed goal [in Baddeley's (1992, 2000) working memory model, this is the *attentional control* of the central executive]. 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 during play in both animals and humans and during enculturation into the norms of culture (Vandervert 2016a) by learning internal models that would implement such changes.]. We hypothesized that the cerebellum does this by *encoding ("learning") temporally ordered sequences* [italics added] of multidimensional 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 (592–93).

I should note that essentially the same predictive and anticipatory functions of the cerebellum for motor, high-level cognitive, and social functions were found independently by Leggio and Molinari (2015). Leggio and Molinari strongly emphasized that the "anticipatory" function of cerebellar internal models is equally important to "prediction." They define this cerebellar-driven anticipation as "the prediction of an incoming behavior effects anticipation—that is, 'the process of formulating and communicating this expectation [prediction] to the cortical areas which become activated prior to the realized event'" (37).

This encoding (or learning) of temporally ordered sequences, then, is precisely the cerebellar mechanism that permits play among animals to train or prepare them for the unexpected. The adaptive advantage of this predictive mechanism (for animals or humans at play, or for humans behaving or thinking in accordance with cultural norms) cannot be overstated. Because it led to science and to our capacity to think in abstractions of any kind, it may be the most powerful advantage produced by evolution. In the title of their article describing these mechanisms, Leggio and Molinari (2015) captured its power: "Cerebellar Sequencing: a Trick for Predicting the Future."

The Cerebellum and Socialization and Imagination during Play and Enculturation

The cerebellum learns mental models (internal cerebellar models) of everything we repeatedly manipulate (Ito 1993, 1997, 2008), and it does this with the ultimate goal of the prediction and anticipation of what is coming next as described by Akshoomoff, Courchesne, and Townsend (1997). For example, the cerebellum learns internal models that control and make more efficient the movement of arms, legs, and fingers, working memory, and so on. In typing, for example, the cerebellum learns models that when sent to the cerebral cortex allow the swift and mostly unconscious control of the keyboard. Cerebellum researchers refer to these manipulated appendages (e.g., fingers) and processes (e.g., working memory) as cerebellar "controlled objects" (Imamizu and Kawato 2012; Ito 2008). Through constant error correction, the cerebellum controls the speed, appropriateness, and consistency of all behavioral and mental functions (Ito 1997, 2008; Schmahmann 1997).

Cerebellum and Socialization: Others as Cerebellar-Controlled Objects

During socialization and enculturation, the conspecifics with which young animals play and the people with whom children or adolescents interact (or even imagine they do: parents, teachers, playmates, etc.) are all cerebellar-controlled objects (Vandervert 2016a). To the cerebellum, another animal or person appears to be no different than an arm, leg, finger, or even, say, a keyboard. That is, the cerebellum learns predictive internal models of real or imagined behavioral, cognitive, and affective interactions with others. So, in the repetitive play of both animals and children and in the repetitive process of enculturation in humans, mental models are formed of the others as cerebellar-controlled objects. These models of other animals and persons unconsciously undergo continual efficiency processing via the five contributions of the cerebellum I have mentioned, and they are continually sent to the cerebral cortex to control either direct action or withhold it depending on the current social circumstances.

The training for the unexpected hypothesis, then, suggests the partners of young animals in play are, to the cerebellum, controlled objects through which a model of the behavior of others can be learned, and, thereby, socialization can take place. That is, through repetition (and only through repetition) are the social patterns of play behavior brought into sync—and young animals and their partners come to share patterns of social behavior. At a higher cognitive level, this would also apply both to human play and enculturation. Doya (1999) offered a description of how the cerebellum learns internal models of words, gestures (and, by definition, working memory) between speaker and listener. In Doya's example, the others are controlled objects that are internalized as a collection of cerebellar internal models and, again, thereby, socialization tales place.

> In the context of communication, the "environment" is the partner of communication [the other person as the controlled object, i.e., the listener] and the goal is to bring the physical or internal state of the partner into a desired state. This involves sequential selection of actions, i.e. words or gestures in an appropriate sequence, in the same way as in the case of many control tasks (fingers, working memory, etc.). When the model of the partner (for example, one's own child or a close friend) is available, the goal can be achieved more readily and quickly. If the internal models of the speaker and listener are similar, communication [and, any related observational learning] is made efficient (970–71).

Note that the other person as a controlled object leads to control not in the sense that the child controls the adult, but rather in the sense that by internalizing the behavior and imagined mental states of the adult, the child learns to come into sync with the expectations, beliefs, and skills of the adult. This occurs in the same way (although not as complexly) a child learns to control a keyboard; the controlled object (the keyboard) is transferred into motor, cognitive, and emotional patterns in a child's nervous system so as to get in sync with its proper operation in relation to words, numbers, and other keyboard functions (see Wolpert, Doya, and Kawato [2003] for more details).

Through cerebellar encoding of the sequential behavior and imagined mental states of others, social interaction leads to countless internal models of other persons as controlled objects in the cerebellum. These, when fed forward to the cerebral cortex, constitute the learned unconscious behavioral, emotional, and mental patterns that make up an individual's culture (Vandervert 2016a). Because the learning of cerebellar internal models for the control of all controlled objects and all combinations of controlled objects is based on the constantly refined prediction and anticipation of future circumstances (Akshoomoff, Courchesne, and Townsend [1997]; Leggio and Molinari [2015]), the cerebellum forms the portion (and arguably the only portion) of the brain that establishes a constantly updated, rule-governed basis for the mental, social, and emotional processes of experience (Vandervert 2016). In particular on the cerebellum's role in establishing rule-governed models of cognitive processes in the prefrontal area of the cerebral cortex see Balsters et al. (2013). I will return to the contribution of the cerebellum to rule-governed thought processes, including imagination.

Vygotsky and the Internalization of Others as Cerebellar-Controlled Objects

It is important to consider Vygotsky's ideas about socialization here. Doya's (1999) view of socialization by communication via the cerebellum is virtually identical to Vygotsky's (1978) notion that communication with another person forms the crucible for the socialization of a child's mind, and this lays the mental, rule-governed groundwork for imagination in play that I discuss. As Vygotsky wrote back in the 1930s:

> Signs and words serve children first and foremost as a means of social contact with other people. The cognitive and communicative functions of language then become the basis of a new and superior form of activity in children, distinguishing them from animals. . . . Through repeated experiences of this type [asking another person for help with a problem], children learn covertly to plan their activities. At the same time they enlist the assistance of another person in accordance with the requirements of the problem before them. The child's ability to *control* [italics added] another person's behavior [much as in Doya (1999)] becomes a necessary part of the child's practical activity. . . . The path from object to child and from child to object passes through another person [as a controlled object]. This complex human structure is the product of a developmental process deeply rooted in the link between individual and social history (28–30).

Vygotsky deserves high praise for anticipating how a child naturally becomes socialized by enlisting the help of another and how that individual, as a controlled object, becomes internalized in the intellectual and skill development of the child.

The Cerebellum's Prominence in the Development of Imagination

The definition of imagination I use comports well with the one employed by Crespi et al. (2016) in their comprehensive study of the relationship between imagination and social cognition: "The term 'imagination' is considered here as the faculty or action of forming new ideas, or images or concepts of external objects not present to the senses, typically derived from creative integration of past experiences, learning, or other information. . . . Production of novelty through imagination thus takes place through deriving elements of verbal or visual thought from perception and memory and combining them in new ways" (182).

This definition of imagination emphasizes new ideas and the creative integration of past experiences. To varying degrees, these critical aspects of imagination involve all five of the contributions of the cerebellum I outlined earlier.

Crespi et al. (2016) further add that imagination can include thinking in inner speech in the prefrontal and parietal areas of the cerebral cortex. These are areas of the cerebral cortex I have described as being richly connected by two-way nerve tracts with the cerebellum (Leiner, Leiner, and Dow 1986, 1989). In regard to inner speech in imagination, Marvel and Desmond (2010) have shown that silent inner speech takes place below the level of awareness in the unconscious working memory (Gilchrist and Cowan 2010) of the cerebellum as subjects imagine they are counting to themselves. Marvel and Desmond (2012) suggested that their definition of inner speech echoes Vygotsky (1986), who proposed that inner speech would be a compressed, largely silent version of speech as we know it. Although inner speech does activate both the dorsal and ventral tracts of the cerebellum's dentate nucleus (Marvel and Desmond 2010), discussion of it lies beyond my scope in this article.

Leiner, Leiner, and Dow (1986, 1989) first suggested that processes of imagination were modeled in the cerebellum. Specifically, they proposed that, in novel situations, an animal would need to process quickly preliminary information mentally before making life or death decisions. Thus, the cerebellum would learn models that rapidly simulate motor and conceptual possibilities and their consequences and then send these to the prefrontal cortex for both unconscious and conscious imaginative processing and action. Such adaptive, rapid sequencing in the mental representations of events would of course constitute the rule-governed, imaginative scenarios in working memory described by Akshoomoff, Courchesne, and Townsend (1997). Balsters and Ramnani (2011) and Balsters et al. (2013) have shown that, indeed, the cerebellum sends rule-governed motor and cognitive models to the prefrontal cortex. Moreover, supporting Leiner, Leiner, and Dow's description of the cerebellum's role in encoding rule-governed imagination, Imamizu et al. (2007)) concluded that cognitive models are blended in the cerebellum during the solving of novel problems. Finally, Imamizu and Kawato (2012) found that the cerebellum becomes active in specific, previously determined, tool-related areas when subjects are asked simply to imagine using any of fifteen everyday tools (hammer, scissors, chop sticks, etc.).

In Vandervert (2011), I hypothesized that the great expansion of the human cerebellum in the last million years coincided with the cerebellar blending of vocalizations with then-existing visual-spatial working memory. This blending, I suggested, was based on progressive tool use (Ambrose 2001; Stout and Chaminade 2012) and eventually resulted in the infinitely partitionable work memory and language. This subdividable, visual-spatial working memory and the unending images it could propagate led to a large increase in human imaginative capability.

Thus, play in animals and play in humans are based on the same mechanisms of rule-governed imagination in the cerebellum, but over the last million years play has transitioned from simple training for the unexpected to long-term survival by predicting, mitigating, and preventing the unexpected. This transition of emphasis toward uniquely human play appears in the expansion in humans of the dentate nucleus from mere motor nerve tracts to motor and cognitive and language nerve tracts to the prefrontal and parietal areas of the cerebral cortex (Leiner, Leiner, and Dow 1986, 1989). The transition also shows up in the mechanism of sequence detection that leads to prediction and anticipation in the cerebellum in humans, which includes working memory (Akshoomoff, Courchesne, and Townsend 1997; Leggio and Molinari 2015). Finally, the transition appears in the use of language and silent inner speech associated with working memory in the cognitive (ventral) dentate in the cerebellum during imaginative thought (Marvel and Desmond 2010b). Further, I propose that this development adaptively continued in human play and was constantly elaborated through the shared practices (beginning, for example, with simple stone tools and rituals) we now call culture (Vandervert 2016a). Both the repetitious sequences required in the making of stone tools and in correctly executing rituals heavily involve the contributions of the cerebellum toward unconscious enculturation.

Put simply, the role of the cerebellum in imagination is as important as its perceptual, motor role in accurately shooting basketballs. That is, the overall picture here of the cerebellum's role in imagination can be understood—as Bostan, Dum, and Strick (2013) argued—for its cognitive functions in general: the "signal from the dentate nucleus to the prefrontal and posterior parietal areas of the cortex [working memory, executive functions, and rule-based imagination] is as important to their function as the signal the nucleus sends to motor areas of the cerebral cortex" (3). Thus, as a sixty-nine billion neuron-strong computational system based on sequence detection leading to prediction and anticipation (Akshoomoff, Courchesne, and Townsend 1997), the human cerebellum wields an unconscious presence in imaginative thought and behavior commensurate with the immense learning requirements and apparently unlimited potential of the experience of socialization during both human play and enculturation.

Imagination in the Zone of Proximal Development and Creativity in the Cerebellum

Although play and culture are based on prediction, anticipation, and rule governance as described by Akshoomoff, Courchesne, and Townsend (1997), they are for the most part imagined states of affairs, imagined realities. That is, within the framework of our definition of imagination (Crespi et al. 2016) involving a child's communication with others (Doya 1999; Vygotsky 1978), play and culture both become a part of the shared, imagined realities of the members of particular cultures. It may sound contradictory to hold that play and culture are equally imaginary, but consider the farfetched, shared beliefs and activities of the many ancient cultures only remotely related to "veridical" reality as we now understand it. One day our current cultures will no doubt seem just as farfetched to members of future cultures who have still a better understanding of the way things really work. All imagination, even if farfetched, is rule governed, and culture is the continuance of the processes of imagination that drive play.

Vygotsky also broadly discussed and supported the idea that rules govern imagination in children's play. After describing research that suggested this, Vygotsky (1978) wrote:

> One could go even further and propose that there is no such thing as play without rules. The imaginary situation of any form of play already contains rules of behavior, although it may not be a game with formulated rules laid

> down in advance. The child imagines himself to be the mother and the doll to be the child, so he must obey the rules of maternal behavior [encoded by the cerebellum during socialization, Doya 1999; Vandervert 2016a]. . . . Whenever there is an imaginary situation in play, there are rules—not rules that are formulated in advance and change during the course of the game but ones that stem from an imaginary situation. Therefore, the notion that a child can behave in an imaginary situation without rules is simply inaccurate. (95)

Vygotsky proposed that these rules are present in all imagination no matter how early in play or how early during enculturation they are encoded in the cerebellum during socialization.

Vygotsky's Zone of Proximal Development: A New Clarification

What is the zone of proximal development (ZPD)? Vygotsky described it as a child's potential contemporaneous span of development.

> *It is the distance between the actual developmental level as determined by independent problem solving and the level of potential development as determined through problem solving under adult guidance or in collaboration with capable peers* [original italics]. . . . If a child can do such-and-such independently, it means that the functions for such-and-such have matured in her. What, then, is defined by the zone of proximal development, as determined through problems that children cannot solve independently but only with the assistance? The zone of proximal development defines those functions that have not yet matured but are *in the process of maturation* [italics added], functions that will mature tomorrow but are currently in an embryonic state (86).

Vygotsky did not further describe an actual mechanism ("in the process of maturation" is not a mechanism) that might underlie and account for the distance between independent problem solving in a child and that which he or she could manage with the help of others.

However, Vygotsky's ZDP can be greatly clarified both by the mechanism of internalization of other persons as controlled objects via the cerebellar encoding of rules I have described (Doya 1999), and by the cerebellar mechanism of the blending of its encoded models. Taken together, these describe how imagination leads to creativity and innovation in problem solving (Imamizu et al. 2012; Vandervert 2015). These two mechanisms of development are also intricately intertwined within the sequence detection and encoding noted by Akshoomoff, Courchesne, and Townsend (1997) and the five contributions of the cerebellum I have described.

We find the intertwining of these two mechanisms whenever a child calls upon another individual for help. When that individual provides help or insights, the child might respond, “Oh, I see how to do it now.” If the insightful suggestion or helpful demonstration effectively exposes the span of the ZPD, it does so because it fits the pattern of internalized models (of other helpers) already encoded internal models of the child’s cerebro-cerebellar system. Thus, the newly suggested model matches (or fails to match) existing cerebellar models already comprising the child’s ZPD. This cerebro-cerebellar system consists essentially of the collaboration of the cerebellum and the prefrontal and parietal areas of the cerebral cortex. The real-time input from the cerebellum as the child watches and contemplates the help offered constitutes the experienced imagination and insight. If the help offered does not fit into the child’s already encoded pattern, it will fall outside his or her ZPD and will not be helpful. For more detailed examples—including simple figure illustrations of the internalization (encoding) of other persons as controlled objects—see Wolpert, Doya, and Kawato (2003).

That a real-time collaboration of the cerebellum and the cerebral cortex drives the ZPD finds strong support in the definition of imagination provided by Crespi et al. (2016) that includes imagined mentation in the prefrontal and parietal cortices. Their definition finds support, in turn, in the decades of research by Ito (1993, 1997, 2008, 2011) on the role of the cerebellum in encoding mental models that are then sent to the prefrontal and parietal areas of the cerebral cortex for action and cognitive experience. These operations of the ZPD are also backed by Marvel and Desmond’s (2010b, 2012) findings about the role of silent inner speech within working memory in the cerebellum and, specifically, its ventral (cognitive) dentate nucleus. Van Overwalle and Mariën (2015), too, concluded that the cerebellum learns internal models for moment-to-moment, predictive “fluent and automatic social interaction” (16). In this research on the solving of new problems, imagination (seen as retrieval processing in silent speech within working memory) occurs in real time within imagined, experimental situations of collaboration between the cerebellum and the prefrontal and parietal cortices.

Vygotsky would very likely agree with these suggestions that imagination in play involves the internalization of models of others as controlled objects and that advances in a child’s development made through the assistance of others must fit the internalization of these models. The cerebro-cerebellar system I have described does exactly this. Consider that, on the relationship between play development and instruction development, Vygotsky (1978) believed:

> Though the play-development relationship can be compared to the instruction-development relationship, play provides a much wider background for changes in needs and consciousness. Action in the imaginative sphere, in an imaginary situation, the creation of voluntary intentions, and the formation of real-life plans and volitional motives—all appear in play and make it the highest level of preschool development. . . . Play creates a zone of proximal development of the child. *In play a child always behaves beyond his average age, above his daily behavior; in play it is as though he were a head taller than himself* [italics added]. As in the focus of a magnifying glass play contains all developmental tendencies in a condensed form and is itself a major source of development. (102)

As Vygotsky argued earlier, rules always govern play. Since rules in games and in neural operations (Akshoomoff, Courchesne, and Townsend 1997; Balsters et al. 2013) specify pathways of actions and thoughts toward solving problems, we can reasonably interpret this to mean that play is always a problem-solving activity. In play, a child—like the animal evolutionarily advanced by virtue of language in Spinka, Newberry, and Bekoff's (2001) definition of play as "training for the unexpected"—always attempts to predict (and make anticipatory adjustments for) what might be coming next. I am arguing that precisely the learning of new models in the cerebellum and the new blendings of these models during play makes a child, as Vygotsky suggested, "a head taller than himself."

The Inevitable Connection between Human Play and Culture

Vygotsky (1978) slyly and quietly proposes what I believe indicates the connection he makes between human play and culture.

> At school age, play does not die away but permeates the attitude toward reality. It has its own inner continuation in school instruction and work (compulsory activity based on rules). It is the essence of play that a new relation is created between the field of meaning and the visual field—that is, between situations in thought and real situations.

> Superficially, play bears little resemblance to the complex, mediated form of thought and volition it leads to. Only a profound internal analysis makes it possible to determine its course of change and its role in development. (104)

One might argue that these words describe a transition from play to a higher order of thought. However, Vygotsky understood that, despite later development in school and work, the "attitude toward reality" is forever encased in the adaptive social reality that produced it. We should recognize that the imagination affected by play within the zone of proximal development must become the imagination that sustains our shared beliefs and attitudes toward the reality within a culture. Thus the zone of proximal development lives on inside culture. Certainly, Vygotsky would have welcomed this interpretation given his affinity for the work of Karl Marx and Frederick Engels (Vygotsky 1978, 6–8).

As animal play evolved toward human play, the cerebellum's dentate nucleus virtually became a river of nerve tracts running from the cerebellum to the areas of the cerebral cortex. And, as it increased the number of nerve tracts intricately interconnecting with cognitive functions, it must also have supported imagination in play and the homologous imagination required during the socialization. We were all, then, from childhood, put in sync by shared beliefs and activities within our culture.

If the cerebro-cerebellar mechanisms behind play and all socialization are the same, as I argue here, then imagination in play does indeed lead to imagination in culture, and in fact, when we take the idea of play to its natural limits as the evolutionary development of the brain's infinite encoding of language (and mathematics), then culture *is* play. There are many signs that strongly indicate that this is the case. The luxurious Roman baths, the playful lifestyle that got Marie Antoinette into trouble, Disneyland and the countless other amusement parks, the theatre, novels, all have thrived in the framework of culture. They become culture. Technology, too, which often arises in play and, as play, becomes culture. And, according to Rose's (2014) description of the "enchanted objects" of technology (iPhones, driverless cars, etc.), we are rapidly approaching experiences of culture that are not significantly different from the play we experienced as children. I would argue further that during the earliest moments of vocalization-related stone tool manufacture (Ambrose 2001; Stout and Chaminade 2012), play-driven technology constituted the "framework-ing" of culture (Vandervert 2011). And as technology grows more refined, it plays an ever larger role in culture until, ultimately (again, as Rose intimates) technology becomes indistinguishable from culture.

Moreover, when we read a novel or watch movies, we all metaphorically play with dolls as children do. Just as a child through playing with a doll imagines rule-governed scenarios involving herself and others, we imagine ourselves and others through the characters and situations within the novel or the film. My point here is that the same mechanisms that originally drove our child's play continue to drive our adult play and our participation in culture. These mechanisms and cultural practices and artifacts create in us an adult, cultural ZPD like the one Vygotsky suggested for childhood. While we inhabit the imaginary world created by the novel or film, we are a cerebellum-driven being who is a "head taller" than we typically are—just as is the case in childhood.

I find another aspect of Vygotsky's zone of proximal development and its relationship to culture interesting here. The same mechanisms that apply to creative development in play within the ZPD can be applied to the hypothetical ZPD I am suggesting at the level of culture as well. In the case of cultures, the ZDP might be defined by paraphrasing Vygotsky: It is the distance between the actual developmental level a culture as determined by independent problem solving by its members and the level of potential development as determined through problem solving under the guidance or in collaboration with extraordinarily capable peers such as Albert Einstein, Picasso, Newton, Edison, Mozart, etc. (choose your favorite genius).

The mechanisms of creativity that produced models of play for an Einstein (or Mozart) would hypothetically be the same in both a child's and a culture's ZPD—namely, the mechanisms that blend cerebellar models toward new levels of prediction (see Vandervert [2015] for details on how this might have worked in the case of Einstein).

Conclusion

Culture may seem to provide the bases for play, but the opposite is true. When viewed from the perspective of intertwined evolutionary paths, especially in the adaptively yoked evolution of motor and cognitive nerve tracts of the cerebellum's dentate nucleus, we see that the brain mechanisms of play have driven culture into existence and continue to drive its advancing forms. Play always leads culture.

We are now beginning to understand the prominent role of the cerebellum in the formulation of unconscious processes that we believe to be behind the executive control of creativity in thought and imagination (Vandervert 2015; Vandervert, Schimpf, and Liu 2007). Specifically, I argue that the massive parallel expansion of the cerebellum and its connections with both motor and cognitive functions in the cerebral cortex over the last million years led to the transition from animal play that was training for the unexpected toward the adaptive prediction and anticipation of future circumstances in human rule-governed imaginative play. With the expansion of the cerebellum came the expansion of rule-governed imagination applied to play.

The Beginning of Culture

Along with the evolution of stone tool technology and use and language (Ambrose 2001; Stout and Chaminade 2012; Vandervert 2011) this capacity for rule-governed, predictive imagination in play accumulated in human society. Given technology and the resulting rule-based patterns of activities and socialization, humans evolved toward shared beliefs and practices that underlie the rule-based components of religions, arts, and sciences. These rule-based components of belief and practice not only predicted future circumstances but lead to shared practices and technology that in early cultures worked to prevent the unexpected from occurring—again, we call these highly adaptive accumulations "culture."

Vygotsky's Zone of Proximal Development

Lev Vygotsky's conception of a zone of proximal development (ZPD) anticipated development of our understanding that the cerebellum constantly employs models of thought process to upgrade a child's capacity to deal with new and more complex problems. We based our conclusion on the cerebellar blendings of cerebellar mental models (Imamizu et al. 2007) and the mechanism of cerebellar sequence detection (Akshoomoff, Courchesne, and Townsend 1997; Leggio and Molinari 2015) toward ongoing creative prediction. Together, these mechanisms lead to forward movement in development during the imaginative activity of play. Moreover, these cerebellar mechanisms can be enhanced by real-time social interaction with teachers and more knowledgeable peers (Van Overwalle and Mariën 2015) which smoothly and automatically helps a child advance within the ZPD.

In addition, Vygotsky's notion that a child is a head taller than himself in play finds strong support in the creative, predictive imagination constantly honed (toward being a head taller) through the blending of models of imagination in the cerebellum, which are then sent to the prefrontal and parietal areas of the cerebral cortex for action or further contemplation.

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