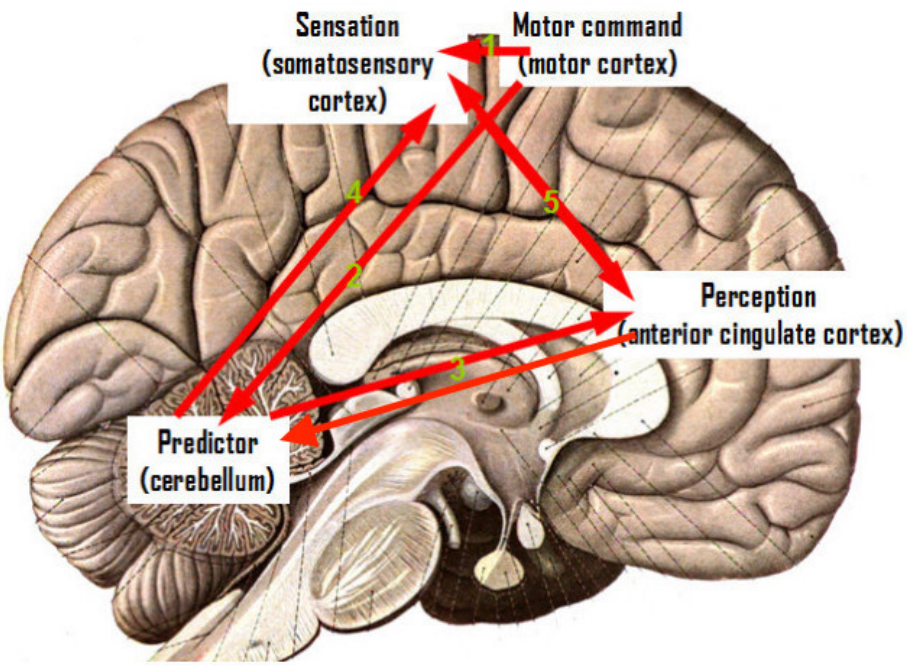
The Genius of the Cerebellum

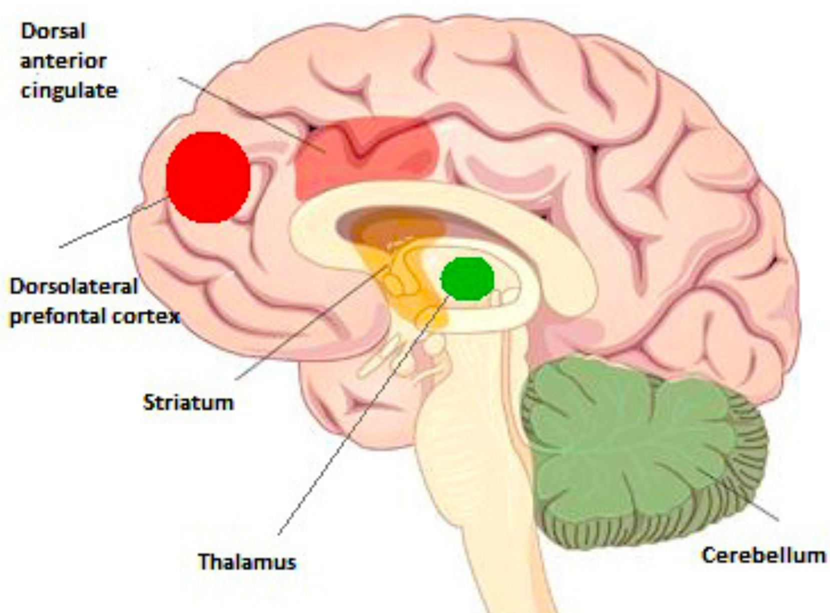


Orchestrating all Cognition

The purpose of this post is to describe how newer understandings of the prominent role of the human cerebellum in the cerebro-cerebellar development of science   and in culture can be extended to provide a way to address the long-standing "mystery" of underpinnings of all cognition…and including the workability of mathematics in the real world.

Based on extensive research studies 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" (Cerebellar networks with the cerebral cortex and basal ganglia)

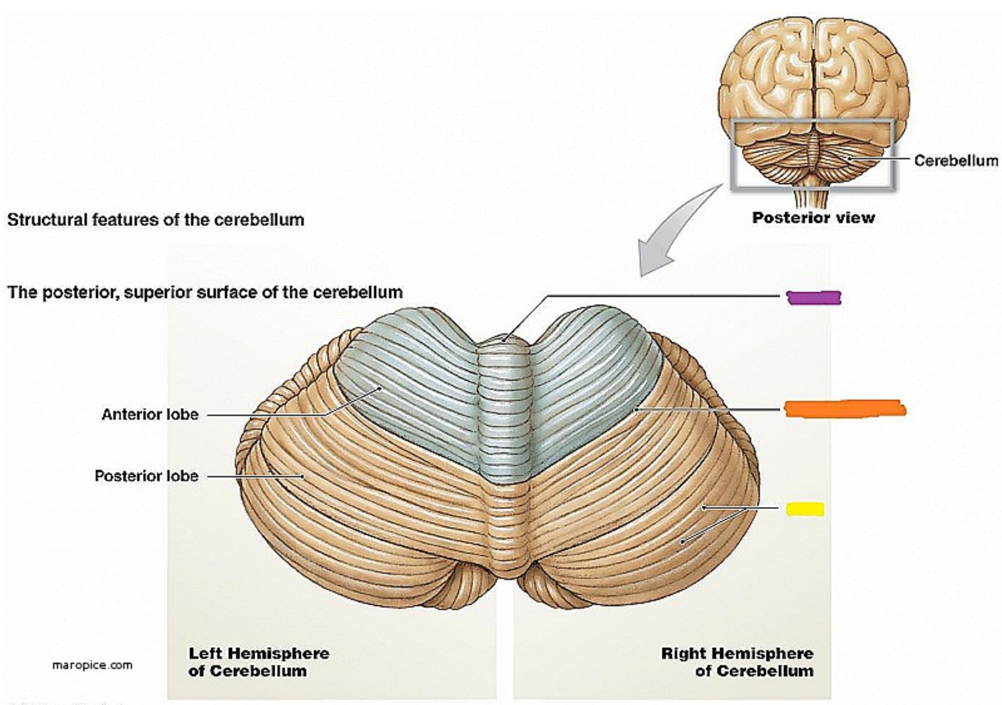
There is a cerebellar mechanism of sequence detection, they show, that is yoked to ontogenetic cerebellar dorsal-to-ventral dentate development as they apply to all forms of movement, cognition



Recent anatomical studies demonstrate that the output of the cerebellum targets multiple nonmotor areas in the prefrontal and posterior parietal cortex, as well as the cortical motor areas. The projections to different cortical areas originate from distinct output channels within the cerebellar nuclei (Cerebellum and Nonmotor Function

The cerebral cortical area that is the main target of each output channel is a major source of input to the channel. Thus, a closed-loop circuit represents the major architectural unit of cerebro-cerebellar interactions. The outputs of these loops provide the cerebellum with the anatomical substrate to influence the control of movement and cognition.

Neuroimaging and neuropsychological data supply compelling support for this view. The range of tasks associated with cerebellar activation is remarkable and includes tasks designed to assess attention, executive control, language, working memory, learning, pain, emotion, and addiction.



These data, along with the revelations about cerebro-cerebellar circuitry, provide a new framework for exploring the contribution of the cerebellum to diverse aspects of behavior.

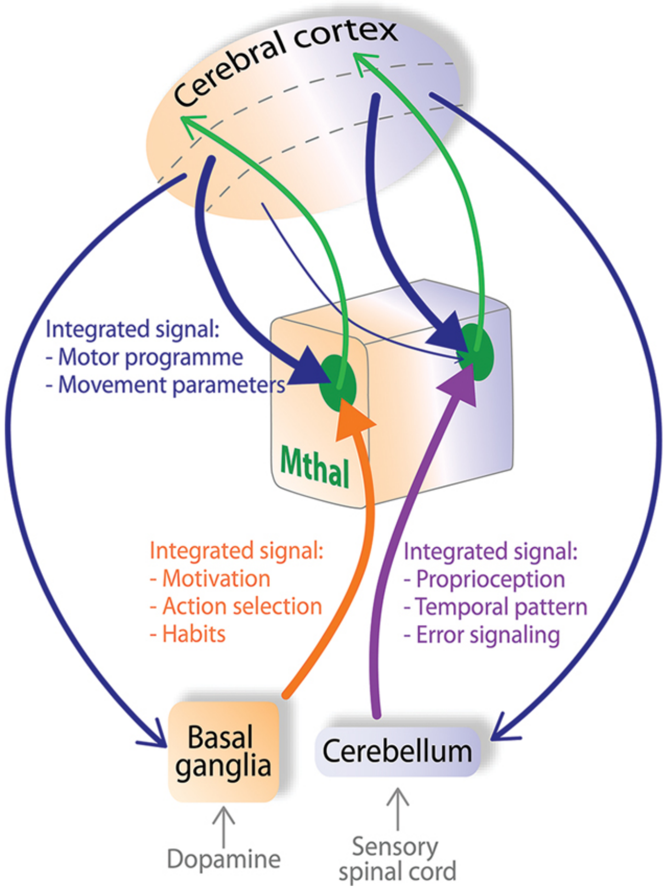
In their watershed articles, Leiner, Leiner and Dow [began by noting that the human cerebellum and its enormous, 69-billion-neuron computational capacity of the cerebellum compared to 16 billion neurons in the cerebral cortex, has increased three- to fourfold in last million or so years.

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 to the parietal and prefrontal areas for planning and language functions (

They proposed back then, not too long ago, 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.

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, These cerebellar internal models consist of distilled or compressed patterns of the movement/thought sequences repeatedly taking place in the cerebral cortex.

According to this rapidly developing view, 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 (The Origin of Mathematics and Number Sense in the Cerebellum)



For this of us who have been interested in the OrbitoFrontal Cortex and the Anterior Cingulate...we can rest arrured that there are super fast direct neuronal connections in a fascinating loop between those areas and the cerebellum

Clinical research has shown that working memory impairments after cerebellar damage and neuroimaging studies have revealed task-specific activation in the cerebellum during working memory processing. A lateralisation of cerebellar function within working memory has been proposed with the right hemisphere making the greater contribution to verbal processing and the left hemisphere for visuospatial tasks

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). Thus, via 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. (Cerebellar Contributions to Verbal Working Memory)

In humans, the ventral dentate is twice as large as the dorsal dentate and is proportionately larger than that of the great apes (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.

It has been 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.

Of the various cognitive domains, the ability to sequence was the most adversely affected in nearly all subjects with cerebellar lesions, supporting the hypothesis that sequencing is a basic cerebellar operation. (The cerebellar cognitive profile)

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.

How can we begin to understand even some of the fascinating depth of complexity that resides in the cerebellum?

The vestibulocerebellum is essential for gaze stability, vestibulo-ocular reflex, and smooth ocular pursuit. Various types of nystagmus, e.g. gaze-evoked nystagmus and saccadic intrusions, which are abnormal fast eye movements that take the fovea off the target, occur following cerebellar damage and result in fixation instability.

Visual-spatial working memory begins to be established by 6 months of age 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 It has been argued that there is 240% increase in the size of the cerebellum in the first year (<u>The role of the pediatric cerebellum in motor functions, cognition and behavior</u>)

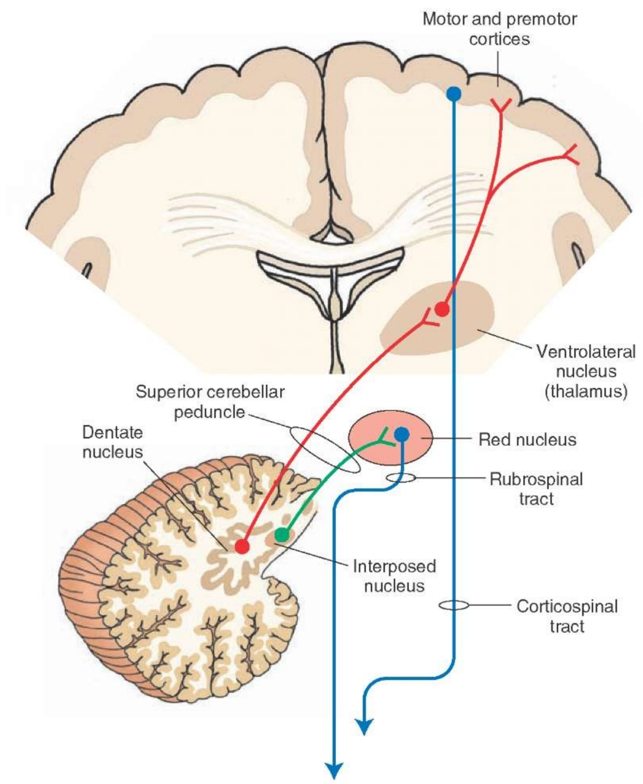
In   working memory tasks, they found the executive control in cerebellar inner speech to be associated with motor planning and preparation related to encoding and retrieval of task information (Marvel & Desmond,

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:

Different cerebellar regions have important roles in voluntary control of limb movements, ocular motor control, balance, walking, and non-motor higher cognitive functions.

Because the cerebellum is critically involved in motor coordination and balance the striking cerebellar growth may underpin the rapid motor developments of infancy.

Given that "cognitive" regions of the cerebellum have reciprocal projections with non-primary 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.



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]

In the past decade, the cerebellum has been reported to encode internal models "that reproduce the essential properties of mental representation in the cerebral cortex"

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.

How does the cerebellum provide these functions?

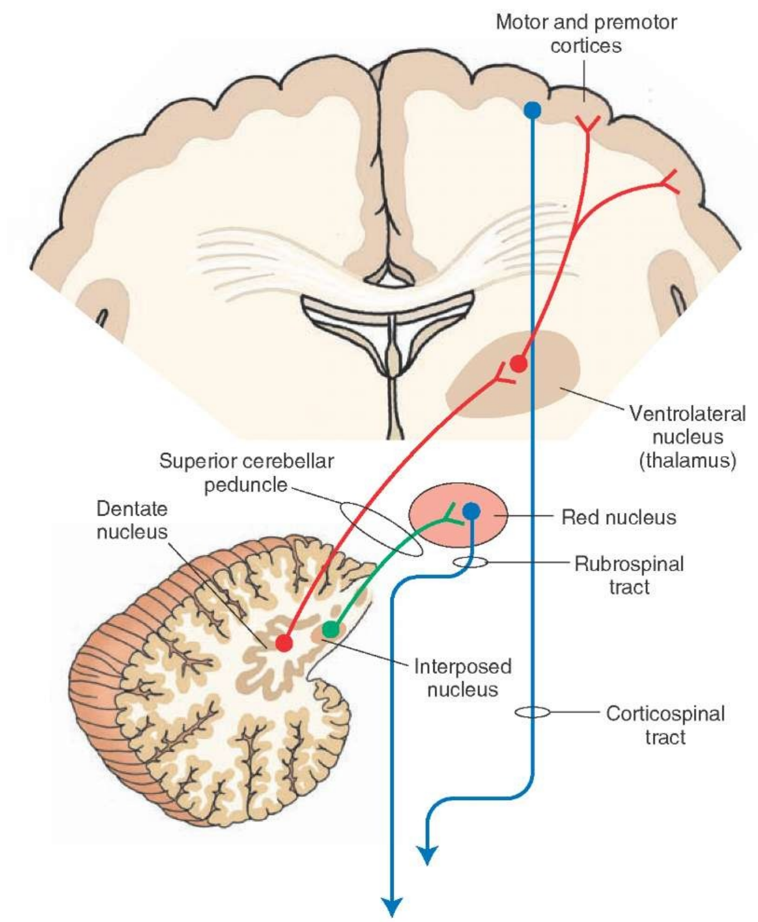
The production of speech, which is a complex process that involves several networks located in the cerebrum and cerebellum. It is a complex process that involves several networks located in the cerebrum and cerebellum. The cerebellar contribution to speech control is likely similar to its control of limb movements.

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]. They are blended in the cerebellum with the infant's vocalizations in the process of language acquisition.

The production of speech involves the coordination of a large number of muscles, in particular the tongue and oro-facial muscles. Inputs from premotor, auditory and somatosensory areas to the cerebellum provide important information for choosing motor commands for speech.

Specifically, the cerebellum plays an important role in speech articulation, prosody (i.e. characteristics of speech style including rhythm, speed, emphasis, and pitch), and planning and processing of speech and language.

For example, it is suggested that in this dorsal-to-ventral dentate manner, the executive use of fingers in counting produces dual, perhaps triple, motor traces in parallel with executive cerebellar inner speech to enhance executive control in working memory. This dorsal-to-dentate scenario would thereby tend to improve (again, not originate) the execution of arithmetic skills.



According to the current prevailing 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) See "Cerebellar Sequencing: a Trick for Predicting the Future"

in motor and non-motor domains, functional state pat- terns are recorded by cerebellar processing and compared with stored templates. If a match is obtained, then it is assumed that the next incoming event can be predicted from the stored template.

Ito 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 non-motor 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 non-motor areas of the cerebral cortex], rendering the control more automatic and less conscious.

Hence, after repeated exercise, one becomes able to move [or think or calculate] quickly, precisely and smoothly without conscious though

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].

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."

It should be noted that this would combine the dorsal and ventral dentate connections with cerebellar lobules VI and VII with loops to/from frontal and parietal areas of the cerebral cortex

Given that "cognitive" regions of the cerebellum have reciprocal projections with non-primary 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

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

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 [15], namely, the premotor cortex, pre-SMA and superior cerebellum (Lobule VI and Crus

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 (

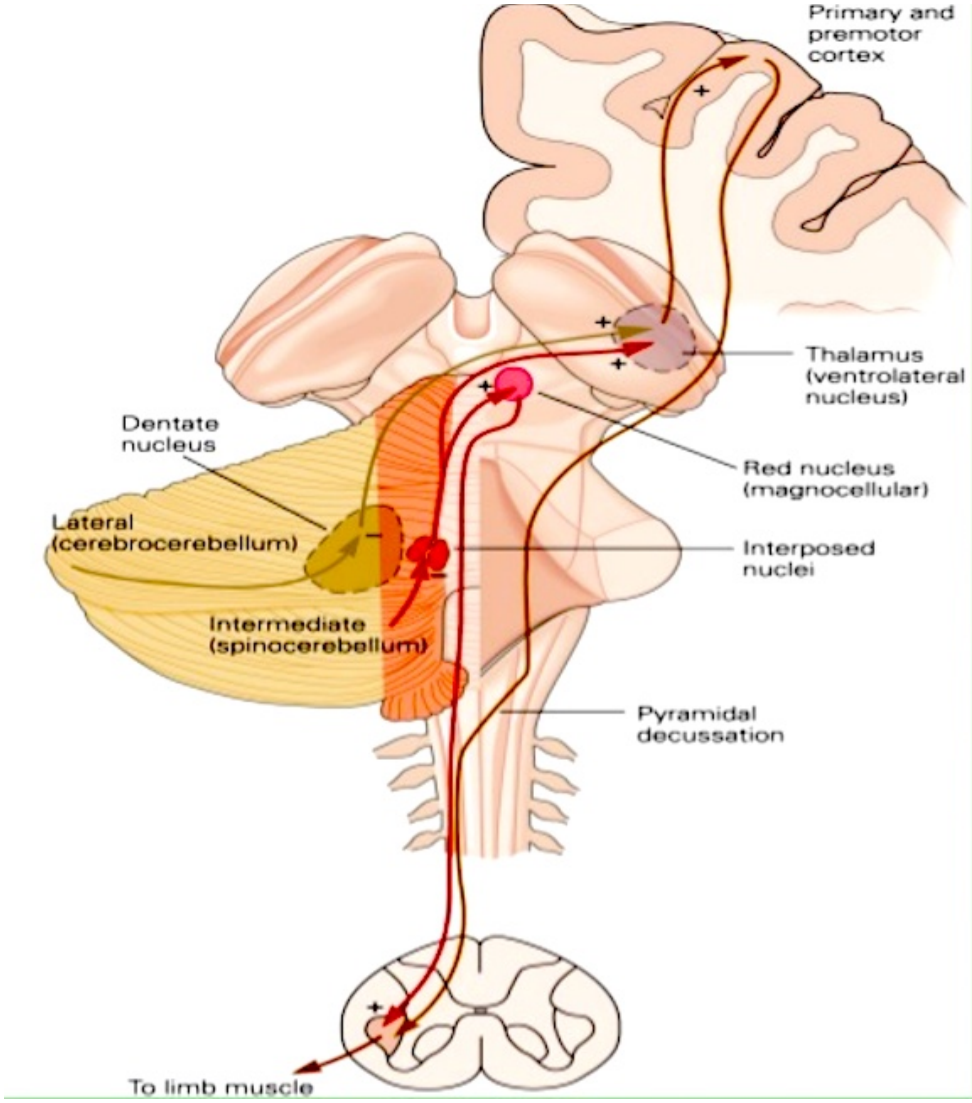
With repetition, these more efficient cerebellar models, operating below the level of conscious awareness, are to the cerebral cortex to bypass the original arduous, time consuming cerebral cortical circuits; the cerebellar models make all movement/mental skills smoother, quicker, and progressively more error-free

"It therefore seems plausible that throughout development the cognitive loop [ventral dentate] retains close ties with its evolutionary precursor, the motor loop [dorsal dentate], which allows both systems to work together, for example by engaging inner speech mechanisms to enhance working memory," (

it is suggested that in this dorsal-to-ventral dentate manner, the executive use of fingers in counting produces dual, perhaps triple, motor traces in parallel with executive cerebellar inner speech to enhance executive control in working memory. This dorsal-to-dentate scenario would thereby tend to improve (again, not originate) the execution of arithmetic skills.

Rather, the cerebro-cerebellar approach brings to bear additional brain mechanisms that may 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

The cerebellar models are also blended within and across skills wherever it will make them more efficient and will allow them to predict complex movement/mental requirements before they occur



In the past decade, the cerebellum has been reported to encode internal models "that reproduce the essential properties of mental representation in the cerebral cortex"

In motor and non-motor domains, functional state patterns are recorded by cerebellar processing and compared with stored templates. If a match is obtained, then it is assumed that the next incoming event can be predicted from the stored template.

In this regard, two explanatory advantages are immediately evident: (1) the "intuitive" character of number sense (Dehaene]) 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 can likewise be parsimoniously and definitively explained in terms of unconscious internal models learned in animal cerebella, which are then sent to their respectively developed cerebral cortices.

The cerebellum has been linked to the representation of temporal information . It has been proposed as a "universal cerebellar transform" that allows to maintain any type of behavior, motor or cognitive, around a homeostatic baseline It has been hypothesized as a sensory coordination of data acquisition

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)

Specifically, presenting sequential violations triggered an increase in activation in the lateral and medial premotor cortex and cerebellum.

The correctness of the predictions is evaluated by comparing the incoming bottom-up information with top-down expectations. If the prediction holds, a signal is sent to alert select cortical areas, allowing the predicted stimulus to be perceived more efficient-

Conversely, presentation of an event that violates expectations effects more widespread brain activation that accelerates the processing of salient sensory information by the changing events and attunes the behavioral response to the new event. In this framework, researchers are examining cerebellar function in the social cognition of patients with autism spectrum disorders (ASDs). Preliminary data indicate altered functional connectivity between the dentate nucleus and the "default mode network," which mediates cognitive processes that are related to social deficits in ASDs.

Lest we take a look at the hippocampus, we also find out that the ability to navigate in the hippocampus is very much dependent on the connection between the hippocampus and cerebellum as well (A hippocampo-cerebellar centered network for the learning and execution of sequence-based navigation.)

Research has revealed a widespread network centered around the cerebral cortex and basal ganglia during the exploration phase, while a network dominated by hippocampal and cerebellar activity appeared to sustain sequence-based navigation.

The learning process could be modeled by an algorithm combining memory of past actions and model-free reinforcement learning, which parameters pointed toward a central role of hippocampal and cerebellar structures for learning to translate self-motion into a sequence of goal-directed actions.