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How the Motor System Integrates with Working Memory

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Abstract

Working memory is vital for basic functions in everyday life. During working memory, one holds a finite amount of information in mind until it is no longer required or when resources to maintain this information are depleted. Convergence of neuroimaging data indicates 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. These “secondary motor” regions are physically located between primary motor and non-motor regions, within the frontal lobe, cerebellum, and basal ganglia, creating a functionally organized gradient. The contribution of secondary motor regions to working memory may be to generate internal motor traces that reinforce the representation of information held in mind. The primary aim of this review is to elucidate motor-cognitive interactions through the lens of working memory using the Sternberg paradigm as a model and to suggest origins of the motor-cognitive interface. In addition, we discuss the implications of the motor-cognitive relationship for clinical groups with motor network deficits.

1. Working memory

Working memory is an active process of holding information in mind, which requires allocation of sustained attention (Fougnie, 2008). When attention is diverted, the information held in mind is rapidly replaced by new internal or external inputs. A popular conceptualization of working memory proposed by Alan Baddeley suggests that a central executive system modulates allocation of attentional resources and manages the manipulation of information (Figure 1A) (Baddeley, 1992). According to Baddeley (1992), the central executive system supervises dual subsystems for holding information in mind: (1) a *phonological loop* for verbal information, and (2) a *visuospatial sketchpad* for visual information (Figure 1A). Each of these subsystems facilitates passive storage of approximately 1–2 seconds. For maintenance of information beyond the temporal limits of

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passive storage, active engagement of attention and rehearsal is required (e.g., repeatedly stating the information out loud). The maintenance phase continues long enough to complete the current task or until attention resources are exhausted. The success and duration of active maintenance depends on attention (Fougnie, 2008), stimulus type (e.g., verbal versus non-verbal) and complexity (Luria et al., 2010), and intrinsic working memory capacity of the subject (Miller, 1956).

Baddeley's model is a helpful tool to represent the conceptual components of working memory but is limited when relating these theoretical features to neural mechanisms. Observing neural responses while participants or non-human animals perform short-term memory tasks first established the prefrontal cortex as crucial for working memory, housing neurons that phasically fire to salient events in working memory assessments (Goldman-Rakic, 1996; Miller and Cohen, 2001). For example, non-human primate cell recordings revealed neurons that fired intensely during the delay period (i.e., between the presentation and recall of information) of a working memory task (Funahashi et al., 1990; Fuster and Alexander, 1971; Goldman-Rakic, 1995). Similar delay-sensitive cell populations within the prefrontal cortex have been confirmed in other models, including rats (Yang et al., 2014) and mice (Kamigaki and Dan, 2017). These results in the frontal cortex were accompanied by similar findings across multiple brain regions, including the posterior parietal cortex (Andersen et al., 1987). These results suggested that a broad network was engaged for the short-term maintenance of information (Constantinidis and Procyk, 2004; Goldman-Rakic, 1988).

Cellular recording studies used to identify the link between working memory and neural mechanisms are limited because the recording areas are small (i.e., electrodes record from a handful of neurons or within several millimeters of tissue, a fraction of the entire central nervous system architecture) and the positioning of electrodes is defined *a priori* by the experimenters. Neuroimaging responds to these challenges of cell recording by measuring changes across large portions of the brain simultaneously and allowing for the assessment of interaction among spatially distant neural networks that otherwise might not be considered integral to the administered task. When a neuroimaging method is coupled with an event-related design, the experimenter can visualize signal changes that represent correlates of neuronal activity in association with particular phases of a process of function. A common working memory paradigm in human neuroimaging is the Sternberg task (Sternberg, 1966), which uses a delayed item recognition protocol (Figure 1B). The Sternberg task involves three main phases: (1) encoding, (2) maintenance (delay period), and (3) retrieval. First, novel stimuli (e.g., a letter array) are presented to the participant (encoding phase). The stimuli then disappear, and the participant is instructed to hold the information in mind for several seconds (maintenance phase). During the maintenance phase, the participant is typically prohibited from using an overt behavioral maintenance strategy to record the stimuli, such as speaking aloud. Finally, a probe is presented (e.g., a letter or symbol), and the subject decides if the probe matches one of the originally presented stimuli (retrieval phase). Examining functional magnetic resonance imaging (fMRI) signal changes associated with each phase of the Sternberg task can reveal the necessary functional regions for normal working memory performance, though other working memory paradigms are also commonly used, such as the N-back and paced auditory serial addition test (PASAT).

The consensus among fMRI studies of working memory largely corroborate findings from electrophysiological recordings that reveal the neural mechanisms of working memory to be represented among canonical cognitive structures, including the prefrontal cortex and posterior parietal attention networks (Owen et al., 2005; Pessoa et al., 2002). However, neuroimaging studies of working memory also find neural correlates that were unobserved in the original cellular studies. Motor regions, including the supplementary motor area (SMA), premotor cortex, basal ganglia, and cerebellum are often simultaneously engaged during the maintenance phase of working memory assessments (Wager and Smith, 2003). While clusters of activations in these regions may be reported in a table of statistically significant activations, they are rarely discussed as relevant to working memory performance. Indeed, the signal observed in motor networks could be interpreted as corresponding to the motor preparation and execution components of a behavioral task. Instead, we argue that currently published neuroimaging data support the conclusion that motor networks are highly integrated into working memory processes and are critical for normal performance.

2. Working memory and the motor network

2.1 Defining secondary motor and non-motor regions within the traditional motor network

The development of neuroimaging methodologies in the late 20th century was crucial for revealing the role of cortical motor regions in cognition (Buckner, 2013). Such studies revealed that non-primary motor regions, including the SMA and premotor cortex, were involved in cognitive tasks, including working memory (Awh et al., 1996; Fiez et al., 1996; Paulesu et al., 1993). For the sake of consistency, we will refer to these non-primary motor regions as “secondary” motor regions. Such regions have been shown to activate immediately prior to motor execution (e.g., button press), suggesting a supportive role, such as planning or preparation, but are not directly responsible for overt motor execution (Hulsmann et al., 2003). In the frontal cortex, secondary motor regions are physically situated between the primary motor cortex and cognitive prefrontal cortex, creating a caudal-to-rostral, motor-to-cognitive functional topography (see Figure 2A). Like the frontal cortex, the subcortical cerebellum and basal ganglia also support both motor and cognition. We propose that these structures contain secondary motor regions spatially organized along a motor-cognitive gradient.

The cerebellum had traditionally been considered a motor structure, but early neuroimaging studies reinforced ongoing speculation that the cerebellum contributed to nonmotor functions (Desmond and Fiez, 1998; Fiez, 1996; Fiez et al., 1996; Petersen et al., 1989; Strick et al., 2009). Evidence suggests that a motor-cognitive functional topography in the cerebellum runs medial to lateral along the coronal plane (Guell et al., 2018b). Cerebellar motor regions include Lobules IV/V with a second motor representation in Lobule VIII, both of which are situated medially, in the anterior and posterior lobes, respectively. Both regions are interconnected to the primary motor cortex (Buckner et al., 2011; Kelly and Strick, 2003). Cognitive regions of the cerebellum include Crus II and Lobule VIIB, which are situated in the lateral aspects of the cerebellar hemispheres and are interconnected to the

prefrontal cortex (Kelly and Strick, 2003; O'Reilly et al., 2010; Stoodley and Schmahmann, 2009). Positioned between these motor and cognitive regions are Lobule VI and Crus I, areas that we propose to be “secondary motor” regions that represent the intersection of motor and cognitive cerebellar function (see Figure 2B). A similar mediolateral topography exists within the second motor representation in Lobule VIII, which can be subdivided into medial VIII B and lateral VIII A, partitioned by the intraviventer fissure (Schmahmann et al., 2000). While VIII B is directly involved in motor execution (Boillat and van der Zwaag, 2019; Stefanescu et al., 2013; Turesky et al., 2018), Lobule VIII A has been associated with speech sequence complexity (Bohland and Guenther, 2006), verb generation (Stoodley, 2012; Thurling et al., 2011), and verbal working memory rehearsal (Chen and Desmond, 2005), extending its functions beyond that of primary motor and suggestive of a secondary motor role. Further supporting this notion, human resting state connectivity studies indicate that the primary motor cortex is functionally connected to Lobule VIII B but not to VIII A (Buckner et al., 2011; Guell et al., 2018a). Additionally, in the dentate nuclei, there is a motor-to-cognitive gradient that runs dorsal to ventral, with a secondary motor region (specifically interconnecting with the SMA) situated in the middle. Taken together, these data suggest there is a topography within the cerebellum that includes regions associated with primary motor, secondary motor, and cognitive functions, organized in a motor-cognitive gradation.

The basal ganglia are a cluster of subcortical nuclei that was once thought to be primarily involved in motor function, but more recently has also become associated with cognition, including working memory (Constantinidis and Procyk, 2004; Leisman and Melillo, 2013). Converging data from human and non-human primate studies indicate the presence of functional imaging gradients within the caudate, putamen, and globus pallidus (GP) separately (see Figure 2C). In the caudate, the medial/anterior region interconnects with the prefrontal cortex (Draganski et al., 2008; Kelly and Strick, 2004). The lateral/caudal region interconnects with the primary motor cortex (Draganski et al., 2008; Kelly and Strick, 2004). The middle region functionally connects with the premotor cortex and pre-SMA (Draganski et al., 2008; Lehericy et al., 2004), suggesting that a secondary motor region is situated between primary motor and cognitive areas within the caudate. Within the putamen, the medial/anterior region interconnects with the prefrontal cortex, while the lateral/posterior region interconnects with the primary motor cortex (Di Martino et al., 2008; Kelly and Strick, 2004; Lehericy et al., 2004). The middle putamen functionally connects with the SMA, pre-SMA, and premotor cortex (Di Martino et al., 2008; Lehericy et al., 2004), representing a region involved in secondary motor functions. Within the GP, the medial aspect interconnects with the prefrontal cortex (Kelly and Strick, 2004; Middleton and Strick, 2002). The lateral GP interconnects with the primary motor cortex (Hoover and Strick, 1999). As in the other basal ganglia nuclei, a middle region of the GP is interconnected with the SMA (Akkal et al., 2007), creating a secondary motor region located between motor and cognitive regions. Thus, based on interpretations of its connectivity with the frontal cortex, the basal ganglia are broadly organized in a gradient fashion that represents a motor-to-cognitive functional topography.

Collectively, these findings indicate that conventional “motor” structures contain sub-regions that cooperatively participate in motor and cognitive processes. Functions are organized along a motor-cognitive gradation and are determined by local topography and

interconnecting brain networks. In this review, we characterize the contributions of the motor network to working memory, with emphasis on the role of secondary motor and non-motor regions within the traditional motor network. Such contributions were evaluated by conducting a review of fMRI event-related working memory studies. By comparing working memory fMRI studies that were similar in methods and analyses, motor networks were consistently found to be active while participants were engaged in working memory rehearsal.

2.2 Literature review: inclusion and exclusion parameters

The Sternberg paradigm enables researchers to directly observe and isolate the neural mechanisms of active rehearsal, which is the core component of working memory. This is possible because during the maintenance phase of the Sternberg paradigm no other stimuli are presented, and no other task demands are required, therefore isolating active rehearsal. In contrast, other working memory tasks elicit processes in addition to rehearsal, such as updating information as new material is continuously presented (e.g., within the N-back or PASAT, etc.). For this reason, this review focuses on findings from studies that have used a Sternberg design. As a result, generalization of findings and interpretations from this review are specific to the Sternberg paradigm and similar behavioral task designs.

Parameters were defined for inclusion regarding the participants recruited, task design, stimulus type, and the field of view for data acquisition. Literature to be included in the review was searched in the PubMed (www.ncbi.nlm.nih.gov/pubmed) database of the US National Library of Medicine. The search terms fMRI AND (Sternberg OR item recognition) resulted in 529 hits. Publications were excluded if they: (1) did not involve an event-related design to isolate the maintenance phase activity, (2) did not report whole-brain activity (i.e., cerebral cortex and cerebellum), or (3) involved an overt motor task simultaneous to the working memory assessment, thereby preventing discrimination of motor activity linked specifically to working memory processes. Studies were included when: (1) healthy adult participants were tested, and (2) the behavioral task design included examination of each of the three Sternberg task phases (encoding, maintenance, and retrieval). To maximize protocol homogeneity among investigations, only studies that visually presented letters, words, pseudo-words, or objects were considered (i.e., paradigms that utilized non-visual stimuli were excluded). A total of 13 neuroimaging studies met these criteria. From these studies, the peak locations of statistically significant clusters during the maintenance phase in primary and secondary motor regions, and cognitive regions within the basal ganglia and cerebellum were compiled (see Table 1). It is worth noting that “whole brain coverage” may not ensure entire coverage of the cerebellum, particularly the inferior aspect of the posterior lobe (e.g., Lobule VIII). Indeed, one study indicated that the field of view excluded the bottom of the cerebellum in some participants (Chein and Fiez, 2001) and one study indicated the possibility of this happening (Bedwell et al., 2005). Three studies specifically took actions to include all of the cerebellum (Chen and Desmond, 2005; Marvel and Desmond, 2012; Peterburs et al., 2019), while the remaining studies did not specify. This inconsistency represents a limitation in the current results; activity in the inferior cerebellum may, in fact, be more robust than reported here.

2.3 FMRI cluster visualization procedure

Coordinates that were originally reported in space normalized to a Talairach template were converted to Montreal Neurological Institute (MNI) space using the Lancaster transform (Lancaster et al., 2007). Anatomical labels were generated for each cluster peak using Analysis of Functional Neuroimaging (AFNI)'s 'whereami' function (Cox, 1996) according to the area of maximum probability from the Eickhoff-Zilles probabilistic cytoarchitectonic atlas and associated macro labels provided with AFNI 18.2 (Eickhoff et al., 2006; Eickhoff et al., 2007; Eickhoff et al., 2005). Within the cerebellum, labels were based on the region of maximum probability from the Spatially Unbiased Infratentorial (SUIT) atlas (Diedrichsen et al., 2009). There were two peaks reported in the original reports that our methods determined to be in white matter; they were therefore excluded from analyses. Peaks were visualized in the MNI coordinate system, overlaid on surfaces provided by the BrainNet Viewer (Xia et al., 2013).

2.4 Motor activity across working memory neuroimaging studies

The blood-oxygen-level dependent (BOLD) signal clusters overall across the selected neuroimaging studies revealed consistent signal increases among motor-related regions whose activity typically reflects pre-movement processes that occur prior to overt motor execution (Hulsmann et al., 2003), including the pre-SMA, SMA, premotor cortex, and lateral regions of the cerebellum (see Figure 3 and Table 1). Noticeably absent was activity in the primary motor cortex (lining the anterior side of the central sulcus; see the primary motor cortex border in Figure 3). This suggests the motor network signal found among these studies did not correspond with overt motor commands and behaviors. A further dissociation was observed such that Broca's area, which is associated with language processing, was specifically activated during the maintenance of verbal information, suggesting that the nature of motor support differed between verbal and non-verbal working memory processes.

These reports suggest that frontal secondary motor regions were recruited during the working memory maintenance phase, in the absence of overt movement and primary motor cortex activation. This functional specificity was replicated in the cerebellum, where lateral parts of the cerebellum were engaged during maintenance, such as Lobule VI, Crus I, and VIIIA, in the absence (with one exception) of activity in primary motor regions within Lobules IV/V and VIIIB. Cognitive cerebellar regions Crus II and 7B were also engaged. Similarly, rehearsal-related activity was observed in the basal ganglia, primarily in the caudate and putamen. It is difficult, however, to determine whether these activations were firmly located in the proposed cognitive and secondary motor sub-regions due to a current lack of defined boundaries for these regions.

The findings from the 13 profiled studies correspond to several fMRI studies that demonstrated that activity in secondary motor regions increased with the number of items held in mind (Chein and Fiez, 2001; Chen and Desmond, 2005; Kirschen et al., 2005; Marvel and Desmond, 2010a) and with stimulus complexity, such as when stimuli were unfamiliar (e.g., pseudowords), shared phonological similarity, or involved a manipulation (e.g., re-ordering items in sequence) (Champod and Petrides, 2007; Chang et al., 2007; Chein and Fiez, 2001; Marvel and Desmond, 2012). Similarly, increased premotor, SMA,

caudate, and secondary motor cerebellar BOLD signal has been associated with increased working memory demands during the “n-back” working memory task, in which subjects were asked to report whether a stimulus had been presented in the preceding trial (lower demand) or presented 2 or 3 trials prior (higher demand) (Callicott et al., 1999; Kuper et al., 2016). These results imply that secondary motor networks may act as a support to working memory performance in the face of elevated cognitive demands.

Additional evidence comes from a verbal working memory fMRI study (Marvel and Desmond, 2012) that compared brain activity during passive storage and active manipulation of letters. During passive storage, participants simply held a target letter in memory. Meanwhile, manipulation required participants to identify the letter that was two alphabetical letters forward of the target letter (e.g., if presented with “a” then two alphabetical letters forward was “c”, or if presented with “k” then “m”). Participants were presented with only two letters in both passive and manipulation conditions, which held the quantity of the load constant. However, the mental representation and rehearsal strategies of those letters differed between conditions as a function of passive storage versus active manipulation. Manipulation of the letters, relative to storage, led to increased secondary motor activity. Moreover, accuracy on the test was negatively correlated with activity in the left premotor cortex and bilateral superior cerebellum, even when only correct trials were included in the analysis. This suggested the secondary motor activity increased because participants were challenged in completing the task (which resulted in overall lower accuracy) but in order to succeed, higher activity was required by these brain regions. Thus, intensity of secondary motor activity scaled with working memory *difficulty*. As supported by the current review, these results from Marvel and Desmond (2012) provide insight that the secondary motor system supports working memory performance, serving as a compensatory aid to ongoing cognitive processes and dynamically changing its activity as one struggles to achieve accuracy in the face of high loads or complex stimuli.

These results focused on healthy individuals, but there are implications of a dynamic motor-cognitive link for clinical groups. For example, damage to secondary motor regions, such as Lobules VI and VIIIA of the cerebellum, may play a role in the subsequently observed working memory deficits (Chiricozzi et al., 2008; Cooper et al., 2012; Stoodley et al., 2016). Likewise, SMA lesions have been associated with verbal working memory impairments, with specific difficulties in information manipulation rather than storage (Canas et al., 2018). In addition, reduced caudate gray matter has been linked to lower working memory performance and reduced caudate activation in adults with attention deficit/hyperactivity disorder (Roman-Urrestarazu et al., 2016).

While we argue that a direct neurophysiological link between non-primary motor function and working memory performance can underlie the deficits observed in these clinical groups, several alternative explanations should be considered. For example, a motor deficit may distract or otherwise impair performance on a working memory task, particularly when a paradigm requires a motor response (Lange et al., 2016). Moreover, disease burden may act as a confounding variable that impairs cognitive performance and amplifies motor network disruption. Finally, it is important to acknowledge that motor impaired clinical groups may exhibit cognitive deficits due to broadly impacted neural networks or loci, as is

the case with several subtypes of ataxia. Therefore, behavioral deficits cannot be easily attributed to disruption of any single region or neural pathway.

2.5 Creation of motor traces during working memory

Neuroimaging reveals that secondary motor networks are involved during working memory maintenance and dynamically change in activity level according to task demands. However, these results do not explain what specific advantages these motor networks offer in working memory. One explanation is that these secondary motor regions support working memory at the cellular level by offering a store of neuronal territory that could be additionally recruited to strengthen signal-to-noise. The recruitment of neurons in secondary motor regions could reduce the likelihood of the maintained information being lost or replaced by off-target stimuli. Alternatively, or in addition, motor networks may influence working memory performance by directly modulating behavior or expanding the number of available rehearsal strategies. There is evidence to support the latter explanation through the creation of *motor traces*.

Motor traces, in this context, are imagined motor representations of salient external or internal information in the absence of overt locomotion (Leisman et al., 2016). For example, internally repeating verbal content or imagining drawing a shape might act as covert motor rehearsal strategies analogous to overt strategies, such as mouthing words or hand tracing (Liao et al., 2014; Marvel and Desmond, 2010b, 2012). Motor traces may reinforce the internal representation of information by offering a redundant rehearsal strategy that can improve the accuracy and duration of maintenance (Koziol et al., 2014). Motor traces may be distinguished from non-motor representations by their role in rehearsal. For example, if the role is to recreate a motor-related association with the information held in mind (e.g., inner speech, inner drawing), then secondary motor regions would engage, in the absence of overt motor actions. However, if the information cannot readily be created into a motor representation, then other regions may be recruited during rehearsal. For example, in a study of verbal working memory for aurally presented unfamiliar backwards speech sounds, the superior temporal sulcus (STS) was engaged during a silent rehearsal phase (Strand et al., 2008). The authors speculated that the STS assisted with covert rehearsal of the novel sounds, an activation that did not occur when verbal content was presented visually (Buchsbaum et al., 2005). The road ahead for testing a hypothesis of dissociable motor and non-motor traces during working memory would include paradigms that relied on contrasting rehearsal mechanisms (e.g., representation of different stimulus modalities) to reveal and characterize the memory traces that separate brain regions or networks engage during rehearsal.

In the context of a Sternberg paradigm, 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. Unlike non-motor representations, motor traces are generated internally. This enables one to hold the information (verbal or non-verbal) in mind for as long as desired, provided that the motor trace can reliably and accurately be re-generated. Supporting this notion, neuroimaging studies of motor imagery (e.g., mental rotation of objects, imagining motor tasks) have revealed activations in secondary motor regions that overlap with those that support working memory (Szameitat et al., 2007; Vingerhoets et al., 2002), which suggests that participants in these neuroimaging studies used imagery of motor actions to assist with information maintenance.

The role of motor traces in working memory is further confirmed by a previous study in which transcranial magnetic stimulation (TMS) was applied to the primary motor cortex, temporarily disrupting its function and that of interconnected secondary motor regions, while participants performed a Sternberg-type working memory task (Liao et al., 2014; Sternberg, 1966). Participants were presented with three stimulus types: (1) real words (e.g., *race, event, girl, usual*), (2) pseudowords (e.g., *opev, severim, shing, derson*), and (3) non-verbalizable symbols (Chinese characters presented to non-Mandarin readers) (see Figure 1B). The authors initially hypothesized that verbal working memory relied on inner speech during active rehearsal, which included the motor speech system. Therefore, they predicted that TMS-induced motor disruption would interfere with verbal working memory at higher loads (difficult to remember pseudowords) but would not impact the lower loads (familiar real words). The authors did not expect to find interference for rehearsal of non-verbalizable symbols because rehearsal in that case would not involve inner speech. Results were consistent with their hypothesis for verbal working memory, demonstrating that motor disruption interfered with rehearsal of pseudowords but not with real words. Counter to their hypothesis, however, motor disruption also interfered with rehearsal of non-verbalizable symbols (Chinese characters). As a control condition, TMS was applied to the visual cortex, which had no effect on working memory performance even though stimuli were presented visually. Thus, working memory disruption was specific to motor system perturbation and was evident in both verbal and non-verbal domains.

Within this same study, post-task surveys were administered to identify participant rehearsal strategies. For verbal working memory, participants reported that they covertly rehearsed words and pseudowords. For non-verbal working memory, participants reported imagining themselves physically recreating the stimuli, such as mentally drawing the symbol. Thus, motor imagery rehearsal strategies were often used to hold non-verbal information in mind. Alternative, less motoric strategies for non-verbal rehearsal were also reported, such as attempting to associate object names to symbols as a mnemonic. Subjects were asked to rate the degree to which they relied on any particular strategy type (verbal or motor). Subjects who reported greater reliance on motor trace strategies experienced more working memory disruption following motor cortex stimulation, while those who relied on non-motor strategies were less affected. Collectively, these data link the motor system to working memory function by demonstrating that perturbations to the motor system can directly interfere with working memory.

Liao and colleagues (2014) argued that the working memory impairments were driven by secondary motor network effects rather than primary motor cortex, due to the absence of overt motor task demands. However, an alternative interpretation suggests a role of the primary motor cortex in working memory function, given that the primary motor cortex was directly targeted by TMS. Indeed, primary motor involvement may play a role in working memory, including low-threshold motor activity (e.g., subtle articulations while rehearsing verbal content). However, converging evidence emphasizes a unique role of secondary motor networks to working memory. Future investigations are needed to directly test primary versus secondary motor cortex contributions to working memory, carefully controlling task demands that may drive motor network engagement (Durisko and Fiez, 2010).

3. Hypothetical origins of motor-cognitive network links

Considering the interaction between cognitive effort and motor system engagement, as represented in working memory, an additional inquiry speculates on the developmental origins and adaptive purpose behind a cognitive system that is supported by secondary motor network activity. Understanding the origins of the motor-cognitive link may help to illuminate the relationship between cognition and motor networks and suggest predictions that can be tested empirically to explain their respective roles. In addition, the origins of these networks links are particularly compelling because of the disparate phylogenetic age of many of these network structures, for example, within the neocortex and cerebellum.

The primary function of any nervous system is to survey a changing environment (sensation) and output a specialized response (motor execution) that aligns with the survival needs of the organism. Indeed, less complex, or evolutionarily early, vertebrates are fundamentally defined by a series of sensory-motor relays, adapted for direct interaction with the environment (Figure 4, Early Brain) (Cisek and Kalaska, 2010). With the absence of cortex, or a canonical cognitive structure, subcortical networks may have been recruited to engage in cognitive processes (Bostan and Strick, 2018). Later in evolutionary development, cognitive networks became available to execute actions associated with executive function, language, and memory. The order of the emergence of these distinct systems (first, sensory-motor, and, second, cognitive networks), suggests that early cognitive networks may have developed directly from the preexisting sensory-motor neural “hardware” (Figure 4, Intermediate Brain) (Buckner and Krienen, 2013; Jacob, 1977; Koziol and Lutz, 2013). Indeed, the most parsimonious evolutionary model for neural development includes novel systems developing from preexisting architecture of the well-established sensory-motor networks (Diamond, 2000). According to this developmental narrative, at very early stages in cognitive development, the neural territory for sensory-motor function and cognition broadly overlapped. As the environment demanded more complex cognitive functions, cognitive networks expanded their territory beyond sensory-motor networks and specialized. The consequence of this developmental narrative is present among recently evolved vertebrates, particularly primates, where cognition and motor regions occupy discrete cortical territories (Figure 4, Developed Brain) (Glasser et al., 2016).

If the timing of this neural network development narrative is accurate, it is possible that earlier connections between cognitive and motor systems have been preserved in the form of

vestigial connectivity. Meanwhile, motor networks that contributed to cognitive performance incurred an evolutionary benefit. For example, holding verbal information in mind over brief delays may have enabled the ability to combine phonemes and attach them to symbolic material, supporting language development (Aboitiz et al., 2006). Evidence for this evolutionary narrative can be found in the anatomy of the primate nervous system. For instance, many pathways bridge motor and cognitive networks, including cortico-cerebellar tracts (Buckner, 2013) and supplementary motor and posterior parietal attention pathways (Blumenfeld, 2002). Function cannot be assumed by the existence of anatomical connections alone. However, functional studies that find connectivity between motor and cognitive structures suggest these anatomical connections, directly or indirectly, carry shared signals (Buckner et al., 2011). Similarly, as described earlier, the cerebellum and basal ganglia are comprised of motor-cognitive functional gradients that suggest a staged addition of network function. In addition, it has been noted that motor and cognitive systems expanded in tandem throughout evolution (Buckner and Krienen, 2013; Diamond, 2000; Dow, 1942). This paired growth is recapitulated in childhood development, during which the prefrontal cortex and posterior-lateral cerebellum are late to reach maturity in early adulthood (Bernard et al., 2016; Diamond, 2000; Tiemeier et al., 2010). In accordance with this well-established structural connection, neuroimaging studies have repeatedly shown that the prefrontal cortex and neocerebellum (the lateral parts of the cerebellum that evolutionarily expanded with the prefrontal cortex) are functionally connected during cognitive tasks, including verbal working memory (Awh et al., 1996; Chen and Desmond, 2005; de Zubicaray et al., 1998; Marvel and Desmond, 2012), attention (Rosenberg et al., 2016), verb generation (Raichle et al., 1994), verbal fluency (Schlosser et al., 1998), and during resting state (Allen et al., 2005; Habas et al., 2009; Krienen and Buckner, 2009; O'Reilly et al., 2010).

In summary, the functional motor-cognitive link may have evolved by building cognitive networks from existing sensory-motor neural architecture, and this development may have been driven by the adaptive advantages of motor-assisted cognition. The resulting architecture is a developed nervous system, as in primates, with examples of both independent and integrated cognitive and motor networks.

4. Clinical implications of motor-cognitive interdependence

Working memory capability varies across individuals (Miller, 1956), which means there is a spectrum of normal ability for the mental maintenance and manipulation of information. Moreover, it is likely that working memory capacity is dynamic within individuals depending on brain state (Yerkes and Dodson, 1908). According to our model, involvement of the motor system in working memory scales inversely with individual working memory capacity. For example, people with lower working memory capacities recruit motor networks more actively and at lower thresholds of cognitive difficulty than do people with higher working memory capacity. This pattern of motor system behavior during working memory may be compared with the Compensation-Related Utilization of Neural Circuits Hypothesis (CRUNCH) that has been put forth in the field of aging research. CRUNCH proposes that, as people age, their cognitive processing becomes less efficient, resulting in hyperactive neural recruitment at lower working memory loads compared to that of younger adults (Reuter-Lorenz and Lustig, 2005). Hyperactive recruitment of the motor system

during working memory has been demonstrated in healthy young adults (Marvel and Desmond, 2012) and by clinical studies when working memory performance was equated between groups, suggesting that clinical populations had to work harder (cognitive effort and/or neural signal amplitude) than healthy controls did to obtain normal working memory performance (Desmond et al., 2003; Forn et al., 2006; Marvel et al., 2012; Reuter-Lorenz et al., 2000; Sweet et al., 2006; Turner and Levine, 2008). However, when working memory performance dropped below that of controls, clinical groups exhibited hypoactivity (Bossong et al., 2012; Mendrek et al., 2004; Mu et al., 2005; Roman-Urrestarazu et al., 2016; Schneider-Garces et al., 2010; Walter et al., 2007). It is unclear whether such hypoactivity is a cause or correlation of the observed low working memory performance. However, it is reasonable to assume that when working memory demands become overwhelmingly difficult, motivation to succeed wanes, along with desire to sustain an effortful strategy. Hence, the rise and fall of neural activity can reflect such working memory constraints (Callicott et al., 1999).

Clinical populations may represent the edge of the spectrum for motor-cognitive interdependence. If working memory is damaged directly (e.g., prefrontal or parietal lesions), this may require greater reliance on the motor system to maintain performance even at intermediate and low memory loads. In addition, we speculate that it may be possible for impairment of motor systems to alter the neural mechanisms of working memory, for example, by limiting motor-based rehearsal strategies, thereby preventing adequate updates in maintenance, or reducing the neuronal territory that would have been recruited for maintenance signaling, thereby reducing signal-to-noise. Motor-cognitive interdependence is an important and under-investigated relationship with clinical implications for cognitive deficits in various movement disorders (e.g., Parkinson's Disease, multiple sclerosis, cerebellar ataxia) and should be rigorously pursued.

Considering clinical observations of people with movement disorders who exhibit cognitive deficits, further research is needed to develop evaluations that specifically test for dual-network interaction deficits, such as the motor and cognitive networks in working memory performance. Current clinical assessments (e.g., Mini-Mental Status Exam) (Folstein et al., 1975) or the Montreal Cognitive Assessment (Nasreddine et al., 2005) may lack the sensitivity to uncover these early and subtle deficits in movement disordered patients. Detecting and treating such cognitive impairments could improve outcomes for these patient populations.

5. Conclusion

A convergence of data from studies utilizing the Sternberg paradigm supports an interaction between motor and cognitive networks in working memory processes. Motor-cognitive interdependence may have originated from motor systems that progressively dedicated neural regions to cognitive demands. The functionality of this interdependence may support an active rehearsal process that serves to lengthen the duration of rehearsal and broaden the type of information that can be held in mind (e.g., non-verbalizable stimuli). This may be accomplished by internally generated motor sequence traces that are actively recreated at will. Disruptions of this motor-cognitive system may contribute to cognitive deficits in a

variety of movement disorders. The results and interpretations presented here have been derived from one particular type of working memory paradigm (Sternberg task) and other working memory tasks may reveal less interaction with the secondary motor system. Nonetheless, the cognitive and clinical neuroscience community would benefit from increased attention to motor-cognitive interactions and consideration of the role of motor networks in working memory and other cognitive functions.

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References

1. Aboitiz F, Garcia RR, Bosman C, Brunetti E, 2006 Cortical memory mechanisms and language origins. *Brain Lang* 98, 40–56. DOI: 10.1016/j.bandl.2006.01.006. [PubMed: 16481035]
2. Akkal D, Dum RP, Strick PL, 2007 Supplementary motor area and presupplementary motor area: targets of basal ganglia and cerebellar output. *The Journal of neuroscience : the official journal of the Society for Neuroscience* 27, 10659–10673. [PubMed: 17913900]
3. Allen G, McColl R, Barnard H, Ringe WK, Fleckenstein J, Cullum CM, 2005 Magnetic resonance imaging of cerebellar-prefrontal and cerebellar-parietal functional connectivity. *Neuroimage* 28, 39–48. DOI: 10.1016/j.neuroimage.2005.06.013. [PubMed: 16023375]
4. Andersen RA, Essick GK, Siegel RM, 1987 Neurons of Area-7 Activated by Both Visual-Stimuli and Oculomotor Behavior. *Experimental Brain Research* 67, 316–322. [PubMed: 3622691]
5. Awh E, Jonides J, Smith EE, Schumacher EH, Koeppel RA, Katz S, 1996 Dissociation of storage and rehearsal in verbal working memory: Evidence from positron emission tomography. *Psychological Science* 7, 25–31. DOI: DOI 10.1111/j.1467-9280.1996.tb00662.x.
6. Baddeley A, 1992 Working Memory. *Science* 255, 556–559. DOI: DOI 10.1126/science.1736359. [PubMed: 1736359]
7. Bedwell JS, Horner MD, Yamanaka K, Li X, Myrick H, Nahas Z, George MS, 2005 Functional neuroanatomy of subcomponent cognitive processes involved in verbal working memory. *Int J Neurosci* 115, 1017–1032. DOI: 10.1080/00207450590901530. [PubMed: 16051547]
8. Bernard JA, Orr JM, Mittal VA, 2016 Differential motor and prefrontal cerebello-cortical network development: Evidence from multimodal neuroimaging. *Neuroimage* 124, 591–601. DOI: 10.1016/j.neuroimage.2015.09.022. [PubMed: 26391125]
9. Blumenfeld H, 2002 *Neuroanatomy through clinical cases*, Second ed. Sinauer Associates, Inc.
10. Bohland JW, Guenther FH, 2006 An fMRI investigation of syllable sequence production. *Neuroimage* 32, 821–841. [PubMed: 16730195]
11. Boillat Y, van der Zwaag W, 2019 Whole brain measurements of the positive BOLD response variability during a finger tapping task at 7 T show regional differences in its profiles. *Magn Reson Med* 81, 2720–2727. DOI: 10.1002/mrm.27566. [PubMed: 30368894]
12. Bossong MG, Jansma JM, van Hell HH, Jager G, Oudman E, Saliassi E, Kahn RS, Ramsey NF, 2012 Effects of delta9-tetrahydrocannabinol on human working memory function. *Biol Psychiatry* 71, 693–699. DOI: 10.1016/j.biopsych.2012.01.008. [PubMed: 22341370]
13. Bostan AC, Strick PL, 2018 The basal ganglia and the cerebellum: nodes in an integrated network. *Nature Reviews Neuroscience* 19, 338–350. DOI: 10.1038/s41583-018-0002-7. [PubMed: 29643480]
14. Buchsbaum BR, Olsen RK, Koch P, Berman KF, 2005 Human dorsal and ventral auditory streams subserved rehearsal-based and echoic processes during verbal working memory. *Neuron* 48, 687–697. DOI: 10.1016/j.neuron.2005.09.029. [PubMed: 16301183]
15. Buckner RL, 2013 The cerebellum and cognitive function: 25 years of insight from anatomy and neuroimaging. *Neuron* 80, 807–815. DOI: 10.1016/j.neuron.2013.10.044. [PubMed: 24183029]

16. Buckner RL, Krienen FM, 2013 The evolution of distributed association networks in the human brain. *Trends in cognitive sciences* 17, 648–665. DOI: 10.1016/j.tics.2013.09.017. [PubMed: 24210963]
17. Buckner RL, Krienen FM, Castellanos A, Diaz JC, Yeo BTT, 2011 The organization of the human cerebellum estimated by intrinsic functional connectivity. *Journal of Neurophysiology* 106, 2322–2345. DOI: 10.1152/jn.00339.2011. [PubMed: 21795627]
18. Callicott JH, Mattay VS, Bertolino A, Finn K, Coppola R, Frank JA, Goldberg TE, Weinberger DR, 1999 Physiological characteristics of capacity constraints in working memory as revealed by functional MRI. *Cerebral cortex* 9, 20–26. DOI: DOI 10.1093/cercor/9.1.20. [PubMed: 10022492]
19. Canas A, Juncadella M, Lau R, Gabarros A, Hernandez M, 2018 Working Memory Deficits After Lesions Involving the Supplementary Motor Area. *Front Psychol* 9, 765 DOI: 10.3389/fpsyg.2018.00765. [PubMed: 29875717]
20. Champod AS, Petrides M, 2007 Dissociable roles of the posterior parietal and the prefrontal cortex in manipulation and monitoring processes. *Proc Natl Acad Sci U S A* 104, 14837–14842. 10.1073/pnas.0607101104. DOI: 0607101104 [pii]. [PubMed: 17804811]
21. Chang C, Crottaz-Herbette S, Menon V, 2007 Temporal dynamics of basal ganglia response and connectivity during verbal working memory. *Neuroimage* 34, 1253–1269. [PubMed: 17175179]
22. Chein JM, Fiez JA, 2001 Dissociation of verbal working memory system components using a delayed serial recall task. *Cereb Cortex* 11, 1003–1014. [PubMed: 11590110]
23. Chen SH, Desmond JE, 2005 Temporal dynamics of cerebro-cerebellar network recruitment during a cognitive task. *Neuropsychologia* 43, 1227–1237. [PubMed: 15949507]
24. Chiricozzi FR, Clausi S, Molinari M, Leggio MG, 2008 Phonological short-term store impairment after cerebellar lesion: a single case study. *Neuropsychologia* 46, 1940–1953. DOI: 10.1016/j.neuropsychologia.2008.01.024. [PubMed: 18342342]
25. Cisek P, Kalaska JF, 2010 Neural mechanisms for interacting with a world full of action choices. *Annu Rev Neurosci* 33, 269–298. DOI: 10.1146/annurev.neuro.051508.135409. [PubMed: 20345247]
26. Constantinidis C, Procyk E, 2004 The primate working memory networks. *Cogn Affect Behav Neurosci* 4, 444–465. [PubMed: 15849890]
27. Cooper FE, Grube M, Von Kriegstein K, Kumar S, English P, Kelly TP, Chinnery PF, Griffiths TD, 2012 Distinct critical cerebellar subregions for components of verbal working memory. *Neuropsychologia* 50, 189–197. DOI: 10.1016/j.neuropsychologia.2011.11.017. [PubMed: 22133495]
28. Cox RW, 1996 AFNI: software for analysis and visualization of functional magnetic resonance neuroimages. *Comput Biomed Res* 29, 162–173. [PubMed: 8812068]
29. de Zubicaray GI, Williams SC, Wilson SJ, Rose SE, Brammer MJ, Bullmore ET, Simmons A, Chalk JB, Semple J, Brown AP, Smith GA, Ashton R, Doddrell DM, 1998 Prefrontal cortex involvement in selective letter generation: a functional magnetic resonance imaging study. *Cortex* 34, 389–401. [PubMed: 9669104]
30. Desmond JE, Chen SH, DeRosa E, Pryor MR, Pfefferbaum A, Sullivan EV, 2003 Increased frontocerebellar activation in alcoholics during verbal working memory: an fMRI study. *Neuroimage* 19, 1510–1520. [PubMed: 12948707]
31. Desmond JE, Fiez JA, 1998 Neuroimaging studies of the cerebellum: language, learning, and memory. *Trends in Neuroscience* 2, 355–362.
32. Di Martino A, Scheres A, Margulies DS, Kelly AM, Uddin LQ, Shehzad Z, Biswal B, Walters JR, Castellanos FX, Milham MP, 2008 Functional connectivity of human striatum: a resting state fMRI study. *Cereb Cortex* 18, 2735–2747. DOI: 10.1093/cercor/bhn041. [PubMed: 18400794]
33. Diamond A, 2000 Close interrelation of motor development and cognitive development and of the cerebellum and prefrontal cortex. *Child Development* 71, 44–56. DOI: Doi 10.1111/1467-8624.00117. [PubMed: 10836557]
34. Diedrichsen J, Balsters JH, Flavell J, Cussans E, Ramnani N, 2009 A probabilistic MR atlas of the human cerebellum. *Neuroimage* 46, 39–46. DOI: 10.1016/j.neuroimage.2009.01.045. [PubMed: 19457380]

35. Dow RS, 1942 The evolution and anatomy of the cerebellum. *Biological Reviews of the Cambridge Philosophical Society* 17, 179–220. DOI: DOI 10.1111/j.1469-185X.1942.tb00437.x.
36. Draganski B, Kherif F, Klöppel S, Cook PA, Alexander DC, Parker GJ, Deichmann R, Ashburner J, Frackowiak RS, 2008 Evidence for segregated and integrative connectivity patterns in the human Basal Ganglia. *J Neurosci* 28, 7143–7152. DOI: 10.1523/JNEUROSCI.1486-08.2008. [PubMed: 18614684]
37. Durisko C, Fiez JA, 2010 Functional activation in the cerebellum during working memory and simple speech tasks. *Cortex* 46, 896–906. [PubMed: 19853247]
38. Eickhoff SB, Heim S, Zilles K, Amunts K, 2006 Testing anatomically specified hypotheses in functional imaging using cytoarchitectonic maps. *Neuroimage* 32, 570–582. DOI: 10.1016/j.neuroimage.2006.04.204. [PubMed: 16781166]
39. Eickhoff SB, Paus T, Caspers S, Grosbras MH, Evans AC, Zilles K, Amunts K, 2007 Assignment of functional activations to probabilistic cytoarchitectonic areas revisited. *Neuroimage* 36, 511–521. DOI: 10.1016/j.neuroimage.2007.03.060. [PubMed: 17499520]
40. Eickhoff SB, Stephan KE, Mohlberg H, Grefkes C, Fink GR, Amunts K, Zilles K, 2005 A new SPM toolbox for combining probabilistic cytoarchitectonic maps and functional imaging data. *Neuroimage* 25, 1325–1335. DOI: 10.1016/j.neuroimage.2004.12.034. [PubMed: 15850749]
41. Fiez JA, 1996 Cerebellar contributions to cognition. *Neuron* 16, 13–15. [PubMed: 8562076]
42. Fiez JA, Raife EA, Balota DA, Schwarz JP, Raichle ME, Petersen SE, 1996 A positron emission tomography study of the short-term maintenance of verbal information. *J Neurosci* 16, 808–822. [PubMed: 8551361]
43. Folstein MF, Folstein SE, McHugh PR, 1975 “Mini-mental state”. A practical method for grading the cognitive state of patients for the clinician. *J Psychiatr Res* 12, 189–198. [PubMed: 1202204]
44. Forn C, Barros-Loscertales A, Escudero J, Belloch V, Campos S, Parcet MA, Avila C, 2006 Cortical reorganization during PASAT task in MS patients with preserved working memory functions. *Neuroimage* 31, 686–691. DOI: 10.1016/j.neuroimage.2005.12.030. [PubMed: 16466933]
45. Fougnie D, 2008 The relationship between attention and working memory, in: Johansen NB. (Ed.), *New research on short-term memory*. Nova Science Publishers, Inc.
46. Funahashi S, Bruce CJ, Goldman-Rakic PS, 1990 Visuospatial Coding in Primate Prefrontal Neurons Revealed by Oculomotor Paradigms. *Journal of neurophysiology* 63, 814–831. [PubMed: 2341879]
47. Fuster JM, Alexander GE, 1971 Neuron activity related to short-term memory. *Science* 173, 652–654. [PubMed: 4998337]
48. Glasser MF, Coalson TS, Robinson EC, Hacker CD, Harwell J, Yacoub E, Uğurbil K, Andersson J, Beckmann CF, Jenkinson M, Smith SM, Van Essen DC, 2016 A multimodal parcellation of human cerebral cortex. *Nature* 536, 171–178. DOI: 10.1038/nature18933. [PubMed: 27437579]
49. Goldman-Rakic PS, 1988 Topography of Cognition - Parallel Distributed Networks in Primate Association Cortex. *Annual Review of Neuroscience* 11, 137–156. DOI: DOI 10.1146/annurev.neuro.11.1.137.
50. Goldman-Rakic PS, 1995 Cellular Basis of Working-Memory. *Neuron* 14, 477–485. DOI: Doi 10.1016/0896-6273(95)90304-6. [PubMed: 7695894]
51. Goldman-Rakic PS, 1996 Regional and cellular fractionation of working memory. *Proc Natl Acad Sci U S A* 93, 13473–13480. [PubMed: 8942959]
52. Guell X, Gabrieli JDE, Schmahmann JD, 2018a Triple representation of language, working memory, social and emotion processing in the cerebellum: convergent evidence from task and seed-based resting-state fMRI analyses in a single large cohort. *Neuroimage* 172, 437–449. DOI: 10.1016/j.neuroimage.2018.01.082. [PubMed: 29408539]
53. Guell X, Schmahmann JD, Gabrieli J, Ghosh SS, 2018b Functional gradients of the cerebellum. *Elife* 7 DOI: 10.7554/eLife.36652.
54. Habas C, Kamdar N, Nguyen D, Prater K, Beckmann CF, Menon V, Greicius MD, 2009 Distinct Cerebellar Contributions to Intrinsic Connectivity Networks. *Journal of Neuroscience* 29, 8586–8594. DOI: 10.1523/Jneurosci.1868-09.2009. [PubMed: 19571149]

55. Hoover JE, Strick PL, 1999 The organization of cerebellar and basal ganglia outputs to primary motor cortex as revealed by retrograde transneuronal transport of herpes simplex virus type 1. *The Journal of neuroscience : the official journal of the Society for Neuroscience* 19, 1446–1463. [PubMed: 9952421]
56. Hulsman E, Erb M, Grodd W, 2003 From will to action: sequential cerebellar contributions to voluntary movement. *Neuroimage* 20, 1485–1492. [PubMed: 14642461]
57. Jacob F, 1977 Evolution and tinkering. *Science* 196, 1161–1166. [PubMed: 860134]
58. Kamigaki T, Dan Y, 2017 Delay activity of specific prefrontal interneuron subtypes modulates memory-guided behavior. *Nat Neurosci* 20, 854–863. DOI: 10.1038/nn.4554. [PubMed: 28436982]
59. Kelly RM, Strick PL, 2003 Cerebellar loops with motor cortex and prefrontal cortex of a nonhuman primate. *J Neurosci* 23, 8432–8444. [PubMed: 12968006]
60. Kelly RM, Strick PL, 2004 Macro-architecture of basal ganglia loops with the cerebral cortex: use of rabies virus to reveal multisynaptic circuits. *Prog Brain Res* 143, 449–459. [PubMed: 14653187]
61. Kirschen MP, Chen SH, Schraedley-Desmond P, Desmond JE, 2005 Load- and practice-dependent increases in cerebro-cerebellar activation in verbal working memory: an fMRI study. *Neuroimage* 24, 462–472. [PubMed: 15627588]
62. Koziol LF, Budding D, Andreasen N, D'Arrigo S, Bulgheroni S, Imamizu H, Ito M, Manto M, Marvel C, Parker K, Pezzulo G, Ramnani N, Riva D, Schmahmann J, Vandervert L, Yamazaki T, 2014 Consensus paper: the cerebellum's role in movement and cognition. *Cerebellum* 13, 151–177. DOI: 10.1007/s12311-013-0511-x. [PubMed: 23996631]
63. Koziol LF, Lutz JT, 2013 From movement to thought: the development of executive function. *Appl Neuropsychol Child* 2, 104–115. DOI: 10.1080/21622965.2013.748386. [PubMed: 23848244]
64. Krienen FM, Buckner RL, 2009 Segregated Fronto-Cerebellar Circuits Revealed by Intrinsic Functional Connectivity. *Cerebral cortex* 19, 2485–2497. DOI: 10.1093/cercor/bhp135. [PubMed: 19592571]
65. Kuper M, Kaschani P, Thurling M, Stefanescu MR, Burciu RG, Gorick S, Maderwald S, Ladd ME, Hautzel H, Timmann D, 2016 Cerebellar fMRI Activation Increases with Increasing Working Memory Demands. *Cerebellum* 15, 322–335. DOI: 10.1007/s12311-015-0703-7. [PubMed: 26202670]
66. Lancaster JL, Tordesillas-Gutierrez D, Martinez M, Salinas F, Evans A, Zilles K, Mazziotta JC, Fox PT, 2007 Bias between MNI and Talairach coordinates analyzed using the ICBM-152 brain template. *Hum Brain Mapp* 28, 1194–1205. DOI: 10.1002/hbm.20345. [PubMed: 17266101]
67. Lange F, Seer C, Dengler R, Dressler D, Kopp B, 2016 Cognitive Flexibility in Primary Dystonia. *J Int Neuropsychol Soc* 22, 662–670. DOI: 10.1017/S135561771600045X. [PubMed: 27333537]
68. Lehericy S, Ducros M, Krainik A, Francois C, Van de Moortele PF, Ugurbil K, Kim DS, 2004 3-D diffusion tensor axonal tracking shows distinct SMA and pre-SMA projections to the human striatum. *Cereb Cortex* 14, 1302–1309. DOI: 10.1093/cercor/bhh091. [PubMed: 15166103]
69. Leisman G, Melillo R, 2013 The basal ganglia: motor and cognitive relationships in a clinical neurobehavioral context. *Rev Neurosci* 24, 9–25. DOI: 10.1515/revneuro-2012-0067. [PubMed: 23241666]
70. Leisman G, Moustafa AA, Shafir T, 2016 Thinking, Walking, Talking: Integratory Motor and Cognitive Brain Function. *Front Public Health* 4, 94 DOI: 10.3389/fpubh.2016.00094. [PubMed: 27252937]
71. Liao DA, Kronemer SI, Yau JM, Desmond JE, Marvel CL, 2014 Motor system contributions to verbal and non-verbal working memory. *Front Hum Neurosci* 8, 753 DOI: 10.3389/fnhum.2014.00753. [PubMed: 25309402]
72. Luria R, Sessa P, Gotler A, Jolicoeur P, Dell'Acqua R, 2010 Visual Short-term Memory Capacity for Simple and Complex Objects. *Journal of Cognitive Neuroscience* 22, 496–512. DOI: DOI 10.1162/jocn.2009.21214. [PubMed: 19301998]
73. Marvel CL, Desmond JE, 2010a The contributions of cerebro-cerebellar circuitry to executive verbal working memory. *Cortex* 46, 880–895. [PubMed: 19811779]

74. Marvel CL, Desmond JE, 2010b Functional topography of the cerebellum in verbal working memory. *Neuropsychol Rev* 20, 271–279. DOI: 10.1007/s11065-010-9137-7. [PubMed: 20563894]
75. Marvel CL, Desmond JE, 2012 From storage to manipulation: How the neural correlates of verbal working memory reflect varying demands on inner speech. *Brain Lang* 120, 42–51. DOI: 10.1016/j.bandl.2011.08.005. [PubMed: 21889195]
76. Marvel CL, Faulkner ML, Strain EC, Mintzer MZ, Desmond JE, 2012 An fMRI investigation of cerebellar function during verbal working memory in methadone maintenance patients. *Cerebellum* 11, 300–310. DOI: 10.1007/s12311-011-0311-0. [PubMed: 21892700]
77. Mendrek A, Laurens KR, Kiehl KA, Ngan ET, Stip E, Liddle PF, 2004 Changes in distributed neural circuitry function in patients with first-episode schizophrenia. *Br J Psychiatry* 185, 205–214. DOI: 10.1192/bjp.185.3.205. [PubMed: 15339824]
78. Middleton FA, Strick PL, 2002 Basal-ganglia ‘projections’ to the prefrontal cortex of the primate. *Cereb Cortex* 12, 926–935. [PubMed: 12183392]
79. Miller EK, Cohen JD, 2001 An integrative theory of prefrontal cortex function. *Annu Rev Neurosci* 24, 167–202. DOI: 10.1146/annurev.neuro.24.1.167. [PubMed: 11283309]
80. Miller GA, 1956 The Magical Number 7, Plus or Minus 2 - Some Limits on Our Capacity for Processing Information. *Psychological review* 63, 81–97. DOI: Doi 10.1037//0033-295x.101.2.343. [PubMed: 13310704]
81. Mu Q, Nahas Z, Johnson KA, Yamanaka K, Mishory A, Koola J, Hill S, Horner MD, Bohning DE, George MS, 2005 Decreased cortical response to verbal working memory following sleep deprivation. *Sleep* 28, 55–67. [PubMed: 15700721]
82. Nasreddine ZS, Phillips NA, Bedirian V, Charbonneau S, Whitehead V, Collin I, Cummings JL, Chertkow H, 2005 The Montreal Cognitive Assessment, MoCA: a brief screening tool for mild cognitive impairment. *J Am Geriatr Soc* 53, 695–699. DOI: 10.1111/j.1532-5415.2005.53221.x. [PubMed: 15817019]
83. O’Reilly JX, Beckmann CF, Tomassini V, Ramnani N, Johansen-Berg H, 2010 Distinct and Overlapping Functional Zones in the Cerebellum Defined by Resting State Functional Connectivity. *Cerebral cortex* 20, 953–965. DOI: 10.1093/cercor/bhp157. [PubMed: 19684249]
84. Owen AM, McMillan KM, Laird AR, Bullmore E, 2005 N-back working memory paradigm: a meta-analysis of normative functional neuroimaging studies. *Hum Brain Mapp* 25, 46–59. DOI: 10.1002/hbm.20131. [PubMed: 15846822]
85. Paulesu E, Frith CD, Frackowiak RS, 1993 The neural correlates of the verbal component of working memory. *Nature* 362, 342–345. [PubMed: 8455719]
86. Pessoa L, Gutierrez E, Bandettini P, Ungerleider L, 2002 Neural correlates of visual working memory: fMRI amplitude predicts task performance. *Neuron* 35, 975–987. [PubMed: 12372290]
87. Peterburs J, Blevins LC, Sheu YS, Desmond JE, 2019 Cerebellar contributions to sequence prediction in verbal working memory. *Brain Struct Funct* 224, 485–499. DOI: 10.1007/s00429-018-1784-0. [PubMed: 30390152]
88. Petersen S, Fox P, Posner M, Mintun M, Raichle M, 1989 Positron Emission Tomographic Studies of the Processing of Single Words. *Journal of Cognitive Neuroscience* 1, 153–170. [PubMed: 23968463]
89. Raichle ME, Fiez JA, Videen TO, Macleod AMK, Pardo JV, Fox PT, Petersen SE, 1994 Practice-Related Changes in Human Brain Functional-Anatomy during Nonmotor Learning. *Cerebral cortex* 4, 8–26. DOI: DOI 10.1093/cercor/4.1.8. [PubMed: 8180494]
90. Reuter-Lorenz PA, Jonides J, Smith EE, Hartley A, Miller A, Marshuetz C, Koeppel RA, 2000 Age differences in the frontal lateralization of verbal and spatial working memory revealed by PET. *J Cogn Neurosci* 12, 174–187. [PubMed: 10769314]
91. Reuter-Lorenz PA, Lustig C, 2005 Brain aging: reorganizing discoveries about the aging mind. *Curr Opin Neurobiol* 15, 245–251. DOI: 10.1016/j.conb.2005.03.016. [PubMed: 15831410]
92. Roman-Urrestarazu A, Lindholm P, Moilanen I, Kiviniemi V, Miettunen J, Jaaskelainen E, Maki P, Hurtig T, Ebeling H, Barnett JH, Nikkinen J, Suckling J, Jones PB, Veijola J, Murray GK, 2016 Brain structural deficits and working memory fMRI dysfunction in young adults who were

- diagnosed with ADHD in adolescence. *European Child & Adolescent Psychiatry* 25, 529–538. DOI: 10.1007/s00787-015-0755-8. [PubMed: 26307356]
93. Rosenberg MD, Zhang S, Hsu WT, Scheinost D, Finn ES, Shen X, Constable RT, Li CS, Chun MM, 2016 Methylphenidate Modulates Functional Network Connectivity to Enhance Attention. *J Neurosci* 36, 9547–9557. DOI: 10.1523/JNEUROSCI.1746-16.2016. [PubMed: 27629707]
 94. Schlosser R, Hutchinson M, Joseffer S, Rusinek H, Saarimaki A, Stevenson J, Dewey SL, Brodie JD, 1998 Functional magnetic resonance imaging of human brain activity in a verbal fluency task. *Journal of Neurology Neurosurgery and Psychiatry* 64, 492–498. DOI: DOI 10.1136/jnnp.64.4.492.
 95. Schmahmann JD, Doyon J, Petrides M, Evans AC, Toga AW, 2000 MRI Atlas of the Human Cerebellum. Academic Press, San Diego.
 96. Schneider-Garces NJ, Gordon BA, Brumback-Peltz CR, Shin E, Lee Y, Sutton BP, Maclin EL, Gratton G, Fabiani M, 2010 Span, CRUNCH, and beyond: working memory capacity and the aging brain. *J Cogn Neurosci* 22, 655–669. DOI: 10.1162/jocn.2009.21230. [PubMed: 19320550]
 97. Stefanescu MR, Thurling M, Maderwald S, Wiestler T, Ladd ME, Diedrichsen J, Timmann D, 2013 A 7T fMRI study of cerebellar activation in sequential finger movement tasks. *Exp Brain Res* 228, 243–254. DOI: 10.1007/s00221-013-3558-5. [PubMed: 23732948]
 98. Sternberg S, 1966 High-speed scanning in human memory. *Science* 153, 652–654. [PubMed: 5939936]
 99. Stoodley CJ, 2012 The cerebellum and cognition: evidence from functional imaging studies. *Cerebellum* 11, 352–365. DOI: 10.1007/s12311-011-0260-7. [PubMed: 21373864]
 100. Stoodley CJ, MacMore JP, Makris N, Sherman JC, Schmahmann JD, 2016 Location of lesion determines motor vs. cognitive consequences in patients with cerebellar stroke. *Neuroimage-Clinical* 12, 765–775. DOI: 10.1016/j.nicl.2016.10.013. [PubMed: 27812503]
 101. Stoodley CJ, Schmahmann JD, 2009 Functional topography in the human cerebellum: a meta-analysis of neuroimaging studies. *Neuroimage* 44, 489–501. [PubMed: 18835452]
 102. Strand F, Forssberg H, Klingberg T, Norrelgen F, 2008 Phonological working memory with auditory presentation of pseudo-words -- an event related fMRI Study. *Brain Res* 1212, 48–54. DOI: 10.1016/j.brainres.2008.02.097. [PubMed: 18442810]
 103. Strick PL, Dum RP, Fiez JA, 2009 Cerebellum and nonmotor function. *Annu Rev Neurosci* 32, 413–434. [PubMed: 19555291]
 104. Sweet LH, Rao SM, Primeau M, Durgerian S, Cohen RA, 2006 Functional magnetic resonance imaging response to increased verbal working memory demands among patients with multiple sclerosis. *Hum Brain Mapp* 27, 28–36. DOI: 10.1002/hbm.20163. [PubMed: 16001441]
 105. Szameitat AJ, Shen S, Sterr A, 2007 Motor imagery of complex everyday movements. An fMRI study. *Neuroimage* 34, 702–713. DOI: 10.1016/j.neuroimage.2006.09.033. [PubMed: 17112742]
 106. Thurling M, Kuper M, Stefanescu R, Maderwald S, Gizewski ER, Ladd ME, Timmann D, 2011 Activation of the dentate nucleus in a verb generation task: A 7T MRI study. *Neuroimage* 57, 1184–1191. DOI: 10.1016/j.neuroimage.2011.05.045. [PubMed: 21640191]
 107. Tiemeier H, Lenroot RK, Greenstein DK, Tran L, Pierson R, Giedd JN, 2010 Cerebellum development during childhood and adolescence: a longitudinal morphometric MRI study. *Neuroimage* 49, 63–70. DOI: 10.1016/j.neuroimage.2009.08.016. [PubMed: 19683586]
 108. Turesky TK, Olulade OA, Luetje MM, Eden GF, 2018 An fMRI study of finger tapping in children and adults. *Hum Brain Mapp* 39, 3203–3215. DOI: 10.1002/hbm.24070. [PubMed: 29611256]
 109. Turner GR, Levine B, 2008 Augmented neural activity during executive control processing following diffuse axonal injury. *Neurology* 71, 812–818. DOI: 10.1212/01.wnl.0000325640.18235.1c. [PubMed: 18779509]
 110. Vingerhoets G, de Lange FP, Vandemaele P, Deblaere K, Achten E, 2002 Motor imagery in mental rotation: an fMRI study. *Neuroimage* 17, 1623–1633. [PubMed: 12414300]
 111. Wager TD, Smith EE, 2003 Neuroimaging studies of working memory: a meta-analysis. *Cognitive, affective & behavioral neuroscience* 3, 255–274.
 112. Walter H, Vasic N, Hose A, Spitzer M, Wolf RC, 2007 Working memory dysfunction in schizophrenia compared to healthy controls and patients with depression: evidence from event-

related fMRI. *Neuroimage* 35, 1551–1561. DOI: 10.1016/j.neuroimage.2007.01.041. [PubMed: 17363277]

113. Xia M, Wang J, He Y, 2013 BrainNet Viewer: a network visualization tool for human brain connectomics. *PLoS One* 8, e68910 DOI: 10.1371/journal.pone.0068910. [PubMed: 23861951]
114. Yang ST, Shi Y, Wang Q, Peng JY, Li BM, 2014 Neuronal representation of working memory in the medial prefrontal cortex of rats. *Mol Brain* 7, 61 DOI: 10.1186/s13041-014-0061-2. [PubMed: 25159295]
115. Yerkes RM, Dodson JD, 1908 The relation of strength of stimulus to rapidity of habit-formation. *Journal of Comparative Neurology and Psychology* 18, 459–482. DOI: DOI 10.1002/cne.920180503.

Highlights

- The primate nervous system exhibits both motor-cognitive links and gradients.
- A convergence of data suggests that the motor network supports working memory.
- Formation of internal motor traces may prolong working memory rehearsal.
- Disrupted motor-cognitive network links may contribute to cognitive deficits.

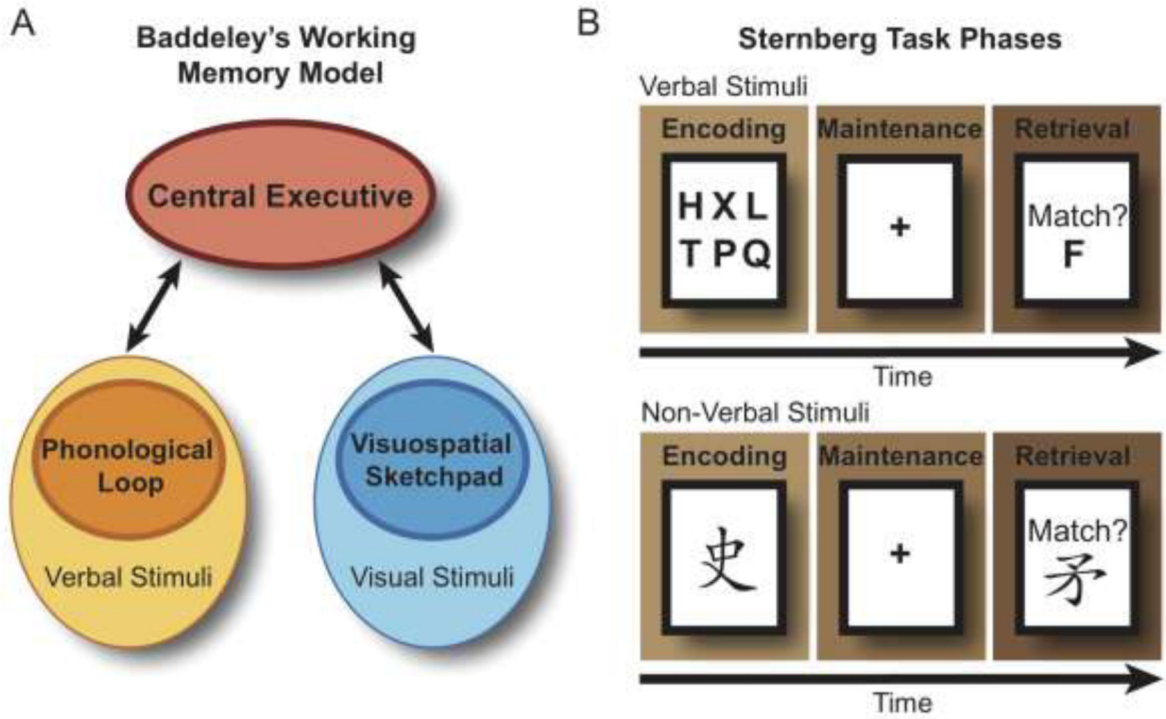


Figure 1.

Baddeley's model of working memory is often tested in the laboratory using the Sternberg Task (Sternberg, 1966). A) Conceptualization of working memory composed by Baddeley consists of a central executive system that supervises a phonological "loop" and a visuospatial "sketchpad" to hold information in mind over brief periods (e.g., seconds). B) 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 non-verbal stimuli. Examples shown are derived from Liao et al., 2014.

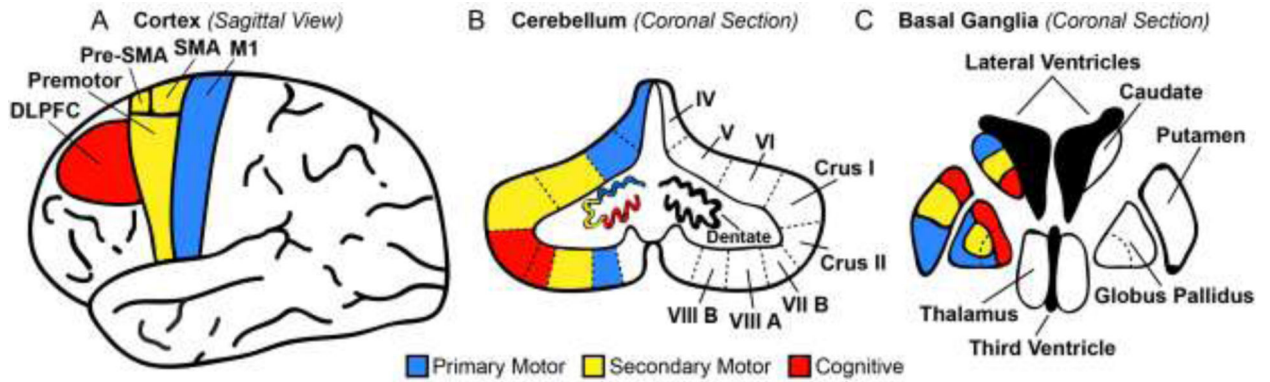
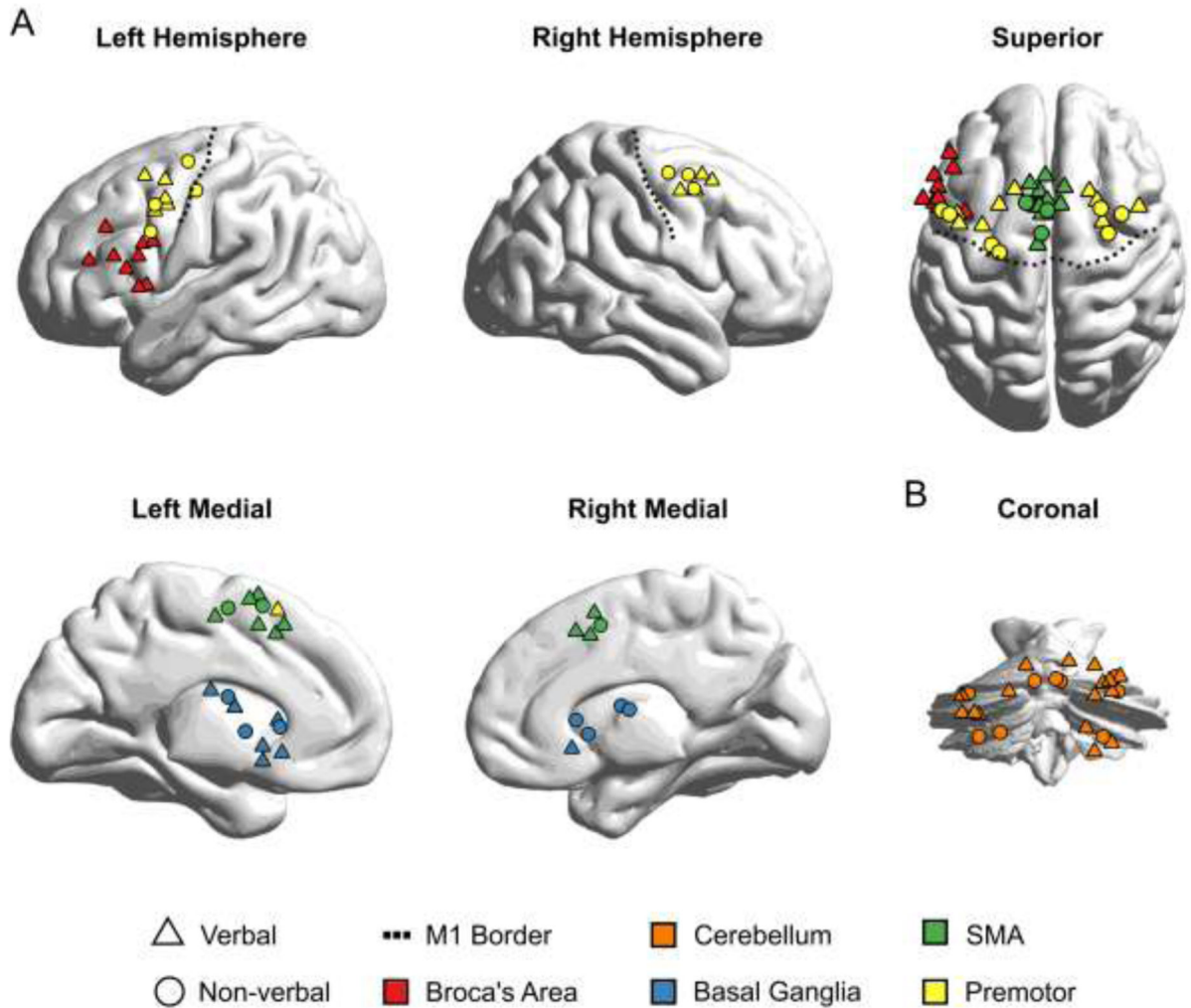


Figure 2.

Functional gradients exist within the frontal lobe, cerebellum, and basal ganglia that range from primarily motor to primarily cognitive. We propose that located within these gradients are “secondary motor” regions that represent the intersection of motor and cognitive functions. Secondary motor regions are typically involved in motor planning and preparation and may support working memory in a similar way by initiating internal motor traces that reinforce the representation of information held in mind. Convergent data across studies indicate that secondary, but not primary, motor areas are active during working memory. A) In the frontal lobe, a functional gradient runs caudal-to-rostral, beginning with the primary motor cortex (M1), to secondary motor regions of SMA, pre-SMA, and premotor cortex, to the dorsolateral prefrontal cortex (DLPFC). B) In the cerebellum, a functional gradient includes primary motor, secondary motor, and cognitive regions that extend medial-to-lateral, and is repeated in the superior and inferior regions of the posterior lobe. A separate functional gradient is represented in the dentate nuclei. C) Within the basal ganglia, each nucleus has its own gradient that is comprised of primary motor, secondary motor, and cognitive functions. DLPFC = dorsolateral prefrontal cortex, SMA = supplementary motor area, M1 = primary motor cortex. Lobule naming in the cerebellum follows the MRI Atlas of the Human Cerebellum by Schmahmann et al., 2000.

**Figure 3:**

FMRI signal peak cluster overlay for working memory maintenance across 13 studies, for (A) the cerebrum and (B) the cerebellum. The activations within motor structures revealed consistent overlap within the basal ganglia (blue), supplementary motor area (SMA, green), premotor cortex (yellow), cerebellum (orange) and Broca's area (red). With the exception of Broca's area, these regions are recruited for both verbal (triangles) and non-verbal (circles) stimuli. The dotted line shows the leading anterior edge of primary motor cortex (M1), according to Eickhoff-Zilles cytoarchitectonic atlas (Eickhoff et al., 2006; Eickhoff et al., 2007; Eickhoff et al., 2005), which was used for anatomical labeling. Note that while one peak, due to its position relative to the brain's outer surface, appears posterior to this line in the left hemisphere view, all peaks were classified as anterior of M1. M1 = primary motor cortex, SMA = supplementary motor area.

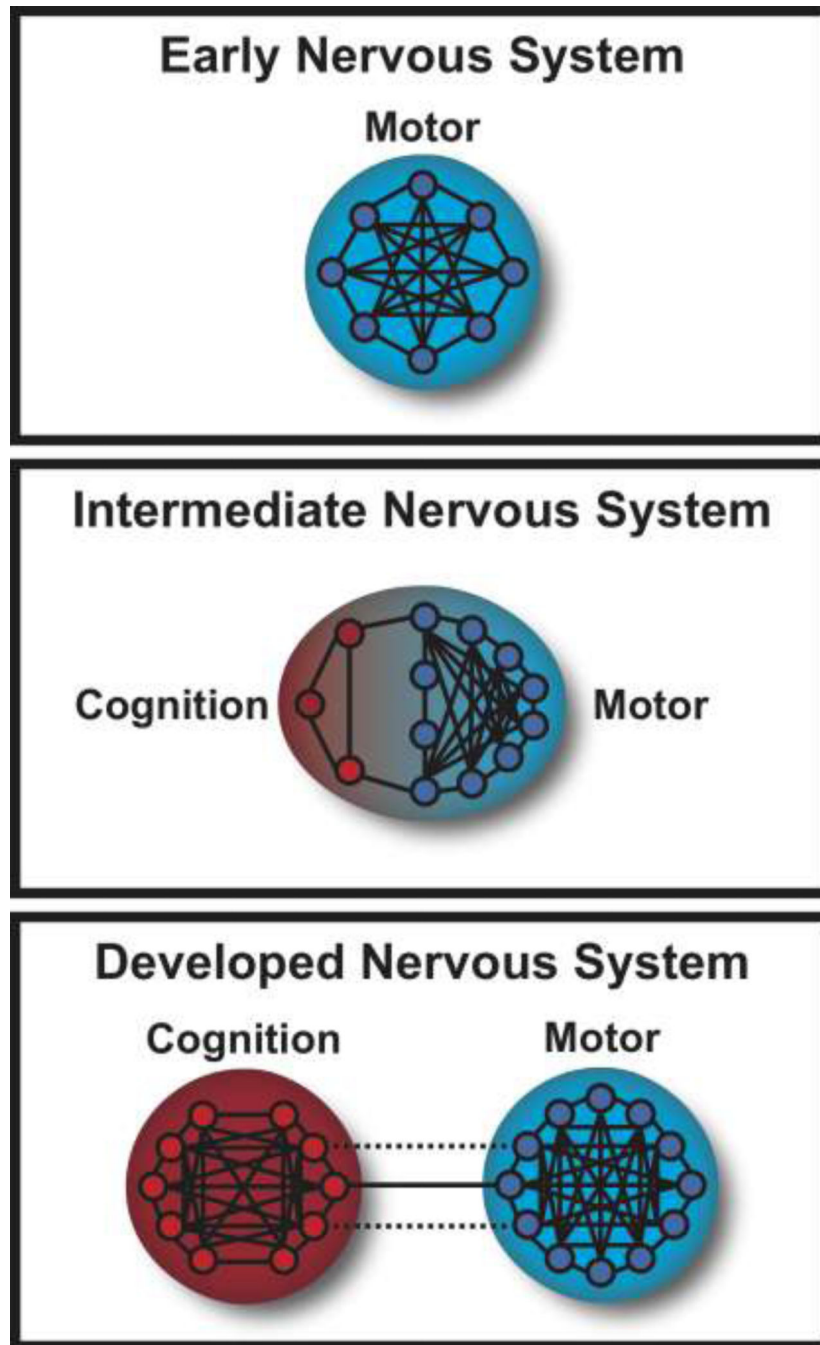


Figure 4. Evolution of motor-cognitive neural linkage. Early brain consisted of a simple sensory-motor system for basic sensing and behaving to a changing environment. Over time, cognitive regions conferred an evolutionary advantage by facilitating abilities such as memory and executive functions, and were built upon existing sensory-motor infrastructure. In the most developed nervous systems (e.g., primates), cognitive and motor regions became specialized and discrete, yet maintained an interdependence.

Table 1.

Overview of studies that met inclusion criteria for this review. Peaks within Brodmann area 6 outside of SMA (Supplementary Motor Area) were classified as “premotor cortex”, and areas within left BA 44 and 45 were classified as “Broca’s area.” Subpeaks within larger clusters are indicated by indentation.

| <i>Study (N)</i> | Brain Region (Brodmann’s Area) | MNI Coordinates | | | Cluster Size (# voxels) |
|-----------------------------------|---------------------------------------|------------------------|----------|----------|--------------------------------|
| | | x | y | z | |
| Verbal | | | | | |
| <i>Bedwell et al., 2005 (14)</i> | | | | | |
| | Broca’s Area (45) | -58 | 24 | 18 | 3 |
| | Right Caudate | 12 | 20 | -5 | 15 |
| | Left Caudate | -16 | 17 | 8 | 6 |
| | Left Putamen | -20 | 19 | -7 | 3 |
| <i>Cairo et al., 2004 (18)</i> | | | | | |
| | Left SMA (6) | -3 | 16 | 48 | - |
| | Left Premotor Cortex (6) | -45 | -1 | 55 | - |
| | Left Premotor Cortex (6) | -16 | 17 | 59 | - |
| | Right Premotor Cortex (6) | 23 | 16 | 55 | - |
| | Broca’s Area (45) | -50 | 36 | 16 | - |
| | Right Cerebellum VI | 31 | -68 | -25 | - |
| <i>Chang et al, 2007(14)</i> | | | | | |
| | Broca’s Area (44) | -56 | 18 | 12 | 3188 |
| | Right Premotor Cortex (6) | 30 | 0 | 50 | 218 |
| | Left Putamen | -20 | 10 | -4 | - |
| | Left Caudate | -18 | -14 | 22 | - |
| | Left SMA (6) | 0 | 4 | 62 | 1276 |
| | Left Cerebellum VI | -16 | -66 | -30 | 229 |
| | Left Cerebellum VI | -8 | -78 | -18 | - |
| | Left Cerebellum Crus I | -38 | -60 | -40 | 113 |
| | Right Cerebellum VI | 28 | -68 | -26 | - |
| <i>Chein and Fiez, 2001 (12)</i> | | | | | |
| | Left Caudate | -14 | -3 | 14 | >5 |
| | Left SMA (6) | 1 | 11 | 50 | >5 |
| <i>Chen and Desmond, 2005(15)</i> | | | | | |
| | Broca’s Area (44) | -64 | 12 | 18 | 860 |
| | Broca’s Area (44) | -56 | 8 | 4 | - |
| | Broca’s Area (44) | -58 | 10 | 24 | - |
| | Left Putamen | -18 | 10 | -11 | 172 |
| | Right Cerebellum Crus II/VIIIb | 20 | -77 | -47 | 149 |
| <i>Habeck et al., 2005 (40)</i> | | | | | |
| | Broca’s Area (44) | -56 | 12 | 3 | - |
| | Left SMA (6) | -5 | 8 | 66 | - |
| | Right SMA (6) | 8 | 9 | 61 | - |

| <i>Study (N)</i> | Brain Region (Brodmann's Area) | MNI Coordinates | | | Cluster Size (# voxels) |
|---------------------------------------|---------------------------------------|------------------------|----------|----------|--------------------------------|
| | | x | y | z | |
| | Right Premotor Cortex (6) | 27 | 11 | 58 | - |
| | Left Premotor Cortex (6) | -24 | 9 | 57 | - |
| | Right Premotor Cortex (6) | 49 | 8 | 50 | - |
| <i>Marvel and Desmond, 2012 (16)</i> | | | | | |
| | Left Premotor Cortex (6) | -46 | 4 | 40 | 1160 |
| | Left SMA (6) | -4 | 8 | 66 | 633 |
| | Left SMA (6) | -8 | 20 | 52 | - |
| | Right SMA (6) | 10 | 18 | 52 | - |
| | Left Cerebellum Crus I | -38 | -60 | -32 | 228 |
| | Right Cerebellum VI | 32 | -60 | -30 | 203 |
| | Right Cerebellum VIIIb | 32 | -70 | -54 | 108 |
| <i>Peterburs et al., 2019 (20)</i> | | | | | |
| | Right Cerebellum VIIIa | 24 | -68 | -58 | 586 |
| | Right Cerebellum VI | 24 | -66 | -18 | 597 |
| | Left SMA (6) | -2 | 4 | 64 | 787 |
| <i>Trapp et al., 2014 (16)</i> | | | | | |
| | Broca's Area (44) | -42 | 5 | 25 | - |
| | Left Premotor Cortex (6) | -45 | -1 | 46 | - |
| | Left SMA (6) | -3 | 8 | 52 | - |
| | Right Cerebellum VI | 36 | -64 | -23 | - |
| | Left Cerebellum Crus II | -30 | -64 | -41 | - |
| | Broca's Area (44) | -42 | 5 | 25 | - |
| <i>Woodward et al., 2006 (18)</i> | | | | | |
| | Broca's Area (45) | -48 | 28 | 32 | 121 |
| | Left SMA (6) | -4 | -12 | 56 | 20 |
| | Left SMA (6) | 0 | 24 | 44 | 158 |
| | Left Cerebellum Crus II | -32 | -68 | -40 | 12 |
| | Right Cerebellum VI | 24 | -64 | -32 | 203 |
| | Right Cerebellum I-IV | 12 | -36 | -16 | 17 |
| Non-Verbal | | | | | |
| <i>Chamod and Petrides, 2007 (11)</i> | | | | | |
| | Left SMA (6) | 1 | 6 | 55 | >110 |
| | Left SMA (6) | -2 | -6 | 60 | >110 |
| | Right Premotor Cortex (6) | 33 | -6 | 59 | >110 |
| | Left Premotor Cortex (6) | -54 | 6 | 30 | >110 |
| | Left Premotor Cortex (6) | -28 | -12 | 64 | >110 |
| | Left Premotor Cortex (6) | -24 | -16 | 50 | >110 |
| | Left Caudate | -16 | -6 | 19 | >110 |
| | Right Caudate | 16 | -4 | 16 | >110 |
| | Left Globus Pallidus | -22 | 2 | 3 | >110 |
| | Right Putamen | 26 | -8 | 14 | >110 |

| <i>Study (N)</i> | Brain Region (Brodmann's Area) | <u>MNI Coordinates</u> | | | Cluster Size (# voxels) |
|------------------------------------------|---------------------------------------|------------------------|----------|----------|--------------------------------|
| | | x | y | z | |
| | Right Cerebellum Crus I | 35 | -58 | -30 | >110 |
| | Cerebellar Vermis VI | 6 | -78 | -24 | >110 |
| | Left Cerebellum Crus I | -35 | -60 | -31 | >110 |
| | Left Cerebellum VIIb | -20 | -72 | -49 | >110 |
| <i>Pollmann and von Cramon, 2000 (9)</i> | | | | | |
| | Left SMA (6) | -10 | 10 | 61 | >100 |
| | Left Premotor Cortex (6) | -50 | 4 | 43 | >100 |
| | Right Putamen | 19 | 12 | 2 | >100 |
| <i>Sobczak-Edmans et al., 2016 (40)</i> | | | | | |
| | Right Premotor Cortex (6) | 40 | 4 | 58 | 134 |
| | Right Premotor Cortex (6) | 29 | 7 | 51 | - |
| | Right Caudate | 8 | 18 | 9 | 40 |
| | Left Caudate | -6 | 18 | 5 | - |
| | Right Cerebellum Crus I | 8 | -76 | -25 | 3940 |
| | Cerebellar Vermis VI | -4 | -76 | -25 | - |
| | Right Cerebellum VI | 34 | -62 | -23 | - |
| | Right Cerebellum VIIb | 28 | -74 | -51 | 291 |
| | Left Cerebellum VIIb | -30 | -74 | -51 | 97 |

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