The Concept of Voluntary Motor Control in the Recent Neuroscientific Literature

Paul Tibbetts, Ph.D. (paul.tibbetts@notes.udayton.edu)
Philosophy and Cognitive Science, University of Dayton
300 College Park, Dayton, OH 45469-1546

Abstract

The concept of *voluntary motor control* (*VMC*) frequently appears in the neuroscientific literature, specifically in the context of cortically-mediated, intentional motor actions. For cognitive scientists, this concept of *VMC* raises a number of interesting questions: *(i)* Are there dedicated, modular-like structures within the motor system associated with *VMC*? Or *(ii)* is it the case that *VMC* is distributed over multiple cortical as well as subcortical structures? *(iii)* Is there any one place within the so-called *hierarchy of motor control* where voluntary movements could be said to originate? And *(iv)* in the current neurological literature how is the adjective *voluntary* in *VMC* being used? These questions are here considered in the context of how higher- and lower-levels of motor control plan, initiate, coordinate, sequence, and modulate goal-directed motor outputs in response to changing internal and external inputs. Particularly relevant are the conceptual implications of current neurological modeling of *VMC* concerning *intentional agency*.

Key Words: causal agency, intentional behavior, motor system, volitions, voluntary motor control, will.

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Despite many years of effort, there is still no complete understanding of the sequence of events that leads from thought to movement, and it is fair to say that the picture becomes increasingly blurred the farther one moves from the muscles themselves. (Purves *et al.,* 1997, p. 292)

More than in sensory systems, our understanding of motor events decreases rapidly as we move from the periphery into the central nervous system. This is a consequence of the fact that there are many pathways converging onto motoneurons from higher centers, and even more onto the higher-order cells. (Nicholls et al., 2001, p. 448)

Volition, Motor Effects, and Neuroscience

Regarding voluntary motor control (hereafter, *VMC*), a primary objective of the historical and contemporary neuroscientific literature is to model how higher- and lower-level structures within the motor nervous system plan, initiate, sequence, modulate, and coordinate voluntary movements (Finger, 1994, pp. 191-239; Jordan & Wolpert, 2000; Passingham, 1993; Purves *et al.*, 2001, pp. 347-441). Accordingly, there are few metaphysical claims made in this literature concerning either the reality or non-reality of volition, choice, or so-called 'acts of will.' Neuroscientists simply assume as a working hypothesis that people can initiate and sustain volitional control over their actions, contingent on normal signal exchange between cortical, subcortical, and spinal-cord motor structures. Consequently, in modeling the processes and computations associated with these structures, we understand what makes *VMC* possible in the first place. So goes the reasoning of much contemporary neuroscientific thinking concerning motor control (Kolb & Whishaw, 1996; Purves *et al.*, 2001; Victor & Ropper, 2001).

How much light this strategy throws on more philosophical concerns regarding volition and choice is, of course, another matter (Brand, 1995). E.g., do volitions and intentions belong to one level of analysis, and motor-system analyses to another? Alternatively, could an account of volitions and intentions be folded into an account of the hierarchy of motor-control structures and computations? To explore this latter possibility requires some understanding of the hierarchy of motor control, from spinal-cord motoneurons to subcortical and cortical structures.

A Preliminary Pass Through the Primate Motor System

Complex, coordinated movements such as reaching for, grasping and writing with a pen require signal sequencing to multiple muscle groups in the shoulder, arm and hand. Such movements are initiated by signals from the primary motor cortex (hereafter, M1) to lower motor neurons in the spinal cord and, in turn, to skeletal muscles. However, M1 output is modulated by input from other motor structures, some cortical (e.g., premotor and prefrontal cortical areas), some subcortical (e.g., basal ganglia and cerebellar inputs). Where some of these inputs to M1 are *internally* generated (such as the motivation to write this manuscript), other M1 inputs are

externally cued (locating the pen and notes with which to begin writing) (Mushiake *et al.*, 1991). However, whether in response to internal or external inputs, M1I outputs to spinal-cord motor neurons and, in turn, to the trunk and limb muscles, are constantly being modulated, updated and, in effect, supervised by a number of motor structures. To achieve even a rudimentary understanding of how this signaling process works, we now examine the voluntary motor system (*VMS*) in somewhat greater detail.

A Second, More Technical Pass Through the Primate Nervous System

As with any other science, the neurological literature regarding motor control is characterized by its own distinctive terminology, methodologies, and causal models. This literature's causal models are particularly complex given: *(i)* the distribution of motor control over a number of cortical and subcortical structures, *(ii)* converging as well as diverging inputs and outputs between these structures, and *(iii)* feedforward and feedback loops within the system. Consequently, the physical and computational complexities of the motor system can only be hinted at in a manuscript of this length (Churchland & Sejnowski, 1992; Georgopoulos, 2000; Jordan & Wolpert, 2000; Tibbetts, 2002).

The *corticospinal* (or pyramidal) *tract* consists of those axons originating in upper motor neurons (UMNs) in more medial areas of M1 and synapse on lower motor neurons (LMNs) in the spinal cord. On the other hand, axons of the *corticobulbar tract* originate in UMNs in more lateral areas of M1. These latter axons synapse on interneurons in the brain stem which, in turn, synapse on cranial nerves to innervate facial muscles (Purves *et al.*, 2001, pp. 18 and 376-381). While some of these descending projections from higher- to lower-motor control levels are associated with *VMC*, other projections provide the requisite stability for voluntary movements (Purves *et al.*, 2001, p. 347). E.g., in deciding to retrieve my dropped pen, my posture must change as I reach down otherwise I will lose my balance. In this example, in response to visual and proprioceptive cues, preprogrammed circuits in the brain stem provide the requisite postural stability. Additionally, my intention to move across the room to where pages of my manuscript have landed also involved central pattern generators (CPGs) in the spinal cord to enable the rhythmic motor patterns associated with walking by alternatively extending and flexing lower limbs (Longstaff, 2000, pp. 213-214).

To summarize the preceding, *VMC* is associated with higher-level cortical areas, particularly with M1 outputs to LMNs in the spinal cord. [Sherrington referred to these LMNs as the 'final common pathway' for voluntary movement and postural stability (Nicholls *et al.*, 2001, p. 449).] However, actual execution of these motor commands, as transmitted by the corticospinal tract, is controlled by local circuitry in the spinal cord. Given these intermediate relay circuits between motor cortex and muscles, there is no *direct* translation of voluntary motor intentions into body movements. Accordingly, while cortical motor areas function in some sort of supervisory and initiating role, there are a number of lower-level, middle managers who exercise discretionary power in how to translate supervisory intentions and commands into goal-directed actions (Zigmond *et al.*, 1999, pp. 931-949).

Regarding these spinal-cord motoneurons and local circuit neurons, for Gazzaniga *et al.* (1998, pp. 379-383), this arrangement:

> is truly hierarchical in that the highest levels need be concerned only with issuing commands to achieve an action, while lower-level mechanisms translate the commands into a movement. [E.g.,] the highest level of the hierarchy need represent only the ultimate goal [reaching for a cup]–the elbow and hand assume a position where the cup can be grasped with minimal effort. How this goal is met does not have to be included in this representation. Lower levels of the hierarchy are concerned with translating a final goal into a certain trajectory.

Following are examples of how different structures within this hierarchy contribute to motor control. UMNs in the motor cortex and brain stem signal to local circuits in the spinal cord to *initiate coordinated, complex movements*. More specifically, UMNs in the premotor cortex *select appropriate goal-directed movements* contingent on internal or external cues (Purves *et al.*, 2001, pp. 384-385). In turn, the premotor cortex receives input from parietal association cortex regarding current, on-going motor responses (Saper *et al.*, 2000, pp. 356-357). *Supervisory control over these cortical outputs* is associated with basal ganglia (inhibitory) output through thalamic relays (Longstaff, 2000, pp. 254-257;). A crucial computational function of these basal ganglia output is *gating and dampening movements* for coordinated behavior (Graybiel *et al.*, 2003). Accordingly, with lesions to the basal ganglia (as in the case of Huntington's and Parkinson's motor disorders), patients "cannot switch smoothly between *commands that initiate a movement* and *those that terminate the movement*" (Purves *et al*., 2001, p. 391, italics added; Victor & Ropper, 2001, pp. 1121-1137).

The basal ganglia also play a supervisory role in: *(i)* suppressing unwanted movements, *(ii)* priming the upper motor circuits involved in initiating voluntary movements, (iii) switching one action for another, and *(iv)* linking cortical motor areas with UMNs in the brainstem (Graybiel *et al.*, 2003). E.g., regarding *(iv)*, for Purves *et al.* (2001, p. 391),

> neurons in this signaling loop between basal ganglia, motor cortex, and brainstem neurons, respond in anticipation of and during movements, and their effects on upper motor neurons are required for the normal initiation of voluntary movements. When one of these components of the basal ganglia or associated structures is compromised, the patient cannot switch smoothly between commands that initiate a movement and those that terminate the movement.

A Specific Example of Voluntary Movement

Let us consider the contribution to voluntary movement of a specific motor structure: the frontal eye fields (FEFs) in the frontal lobes. The FEFs are associated with saccadic eye movements, where the eyes move from one fixation point to another in the visual field. The FEFs project to 'saccade-related burst neurons' in the intermediate layer of the superior colliculus (SC) which, in turn, project to cranial nerves in the brain stem and then to extraocular muscles. Lesions to the FEFs result in an inability to *initiate* voluntary shifts from one external visual target to another (Purves *et al.*, 2001, p. 437).

The respective contributions of FEFs, M1, and the lateral and medial premotor areas, to voluntary eye movements are illustrated in the following example of locating and retrieving my coffee cup: *(1)* The medial premotor cortex (associated with internal, including intentional and motivational cues to locate the cup) selects appropriate goal-directed movements which, in turn, signal UMNs in M1. (Regarding the contribution of posterior parietal association cortex to intentions, see Anderson *et al.,* 2002, and Snyder *et al.,* 1997.) In turn, M1 signals the cranial (accessory) nerve for head and neck movements. *(2)* Visually searching for my cup amidst the books and clutter on the desk involves the FEFs and saccadic eye movements. *(3)* As the cup is located, providing external cues for motor control, output to M1 shifts from medial to more lateral premotor cortices. *(4)* Stabilizing the retinal image of the cup on the fovea as I shift my head and body involves smooth-pursuit eye movements and vestibulo-ocular involuntary reflexes. *(5)* Reaching for the cup is initiated by motor neurons in those areas of M1 where head, neck, arm and hand muscles are cortically represented. Reaching for the cup when the cup is in full view involves the *premotor* cortex (Fitzgerald & Folan-Curran, 2002, p. 250). *(6)* Additionally, there is the contribution of the posterior parietal cortex in coordinating sensorimotor transformations (Wurtz & Kandel, 2000, p. 567). *(7)* Initiating arm and shoulder movements involves the corticospinal tract, interneurons, and motoneurons in the spinal cord. *(8)* The basal ganglia exercises supervisory control over these cortical inputs by dampening excessive arm movements to ste*ady* the cup. Clearly there is more to intentionally reaching for my cup than M1 output to motoneurons in the spinal cord! (Gazzaniga *et al.*, 1998, pp. 375-378; Ivry & Fiez, 2000; Victor & Ropper, 2001, pp. 53-55; Zigmond *et al.*, 1999, pp. 946-947.)

A Philosophical Objection: The Confusion of Intentional Causes With Material Conditions

> If someone said that without bones and sinews and all such things, I should not be able to do what I decided, he would be right, but surely to say that they are the cause of what I do, and not that I have chosen the best course...is to speak very lazily and carelessly. The cause of my sitting here [in this cell] with my limbs bent is that, after the Athenians decided it was better to condemn me, for this reason it seemed best to me to sit here and more right to remain and to endure whatever penalty they ordered. Imagine not being able to distinguish the real cause from that without which the cause would not be able to act as a cause.
>
> --Socrates, *Phaedo* (98c-99b)

In the preceding quote, Socrates (Plato) distinguished between *(i)* the *causes* of his actions (i.e., his decisions and intentions) and *(ii)* the bodily *conditions* ('bones and sinews and all such things') by which *(i)* are expressed and instantiated. Plato therefore anticipated the later distinction between actions and movements or, more accurately, between *a language of actions* and *a language of movements* (Searle, 1996). A language of actions, with its reference to intentions, choices and desires, is clearly not synonymous with physical descriptions of 'bones, sinews and all such things.'

Let us now extend this account of actions and movements to Plato's distinction between *(i)* the (intentional) causes as against *(ii)* the (material) conditions for acting. On his account, causes and conditions belong to different descriptive and, it would appear, different explanatory languages; namely, the (intentional) language of actions and the (scientific, i.e., physicalistic) language of movements. If, as Plato claimed, the two languages are not inter-translatable then the explanatory language of intentions and actions is semantically complete and independent of references to material (bodily) considerations, including the motor system in general. If we adopt this two-languages strategy we are saying, in effect, that motives, intentions and choices can not be causally modeled by either the physical or the computational languages of neuroscience.

In response, the concept of *VMC* (which is associated with the language of intentions) is in fact currently modeled in the vocabulary of neuroscience. Consequently, *either (i*) the language of intentions and the language of neuroscience are (at least for some concepts) inter-translatable, *or (ii)* the concept of *voluntary* in *VMC* is simply empty of intentional content *as currently employed in the neuroscientific literature*. In defense of *(i)*, examples of the translation of intentional into neurological language is at least implicit in the following (emphasis added): *(a) Self-initiated movements* and *the encoding of intentions* (Purves *et al.*, 2001, p. 385). *(b)* The role of multiple cortical areas as 'the brain generates a *voluntary movement*' (Zigmond *et al.*, 1999, p. 941). *(c)* The neural planning and initiation of *goal-directed movements* (Nicholls *et al.*, 2001, pp. 464-468). And *(d)* "planned, learned, skilled, *purposeful movements* that depend heavily, among other sources, on premotoneurons in the cerebral cortex" (Slaughter, 2002, p. 173).

Claims *(a)-(d)* implicitly share certain assumptions: *(i)* the motor encoding of intentions and, in turn, *(ii)* operationalizing the concept of voluntary control in terms of voluntary *motor* control; *(iii)* operationalizing *VMC* in terms of control and processing within subcortical as well as cortical motor structures. Combining *(i)-(iii)* we derive *(iv)*: A strictly neurocomputational account of causal agency.

A Distributed Account of *VMC*

On Plato's line of reasoning, the study of motor systems is as irrelevant to understanding intentional actions as is the study of the mechanical workings of an automobile to understanding the driver's decisions to take one road rather than another. However, this driver/vehicle analogy only makes sense if intentional systems are *in* the nervous system in the way drivers are *in* vehicles, that is, as cause-initiating agents. But perhaps we are not *in* our nervous systems but *are* those systems! Ironically, this alternative was suggested by Descartes, the philosopher historically most associated with a dualism between cognitive agency and that agent's body (Cottingham, 1995, pp. 193-195). In his *Meditations on First Philosophy* (1641/1988, p. 116), Descartes alluded to a non-dualist alternative regarding agents and their bodies:

> Nature also teaches me, by these sensations of pain, hunger, thirst and so, that I am not merely present in my body as a sailor [or pilot] is present in a ship, but that I am very closely joined and, as it were, intermingled with it, so that I and the body form a unit.

If, to use Descartes' language, we are 'intermingled with our bodies to form a single unit,' then it appears arbitrary to exclude the motor system, particularly the motor system associated with voluntary control, from this 'single unit.' Given that, on Descartes' model, the pilot is intermingled as a single unit with his ship, Plato's supposed distinction between intentional causes, as against the material conditions by which those intentions are instantiated and realized, would be conceptually blurred. In other words, there would be no place one could point to and say, 'this causes that' or 'this is the (intentional) cause and that the (material) condition.'

One traditional metaphysical name for a non-material, intentional agency has been 'the Will' (Flanagan, 2002; O'Shaughnessy, 1994). Alternatively, the literature on motor control surveyed in this paper suggests a purely neurological reconstruction in terms of: *(i)* the distribution of motor control over a number of cortical, subcortical, brainstem and spinal-cord structures within the motor system, *(ii)* feedforward and feedback information loops between different processing modules within this hierarchy, responding *(iii)* to internal or external cues and triggers (Jordan & Wolpert, 2000; Mushiake *et al.*, 1991). Given *(i)-(iii)*, it may therefore constitute a conceptual as well as an empirical error to identify any one processing structure within the motor-system network as *the* place where intentions and voluntary movements causally originate and are supervised. So, perhaps the concept *voluntary* in *VMC* simply denotes cortically-supervised and cortically-mediated motor responses to the internal and external inputs noted earlier. Perhaps *VMC* in this sense is the neurological equivalent of Plato's causal agent/agency!

One further point regarding motor control. The voluntary motor system (*VMS*) is frequently modeled in the neuroscientific literature in terms of higher- as against lower-level motor-control processors and therefore as an hierarchical system. In turn, a hierarchical model implies that system commands originate at the top of the system and then relayed to lower-level control modules. However, this pyramid of control metaphor has not gone unchallenged. E.g., for Cotterill (1998, p. 58; emphasis added),

> The trouble with such a picture is that one is ultimately confronted with the need to put a label on the pyramid's uppermost point. But it is possible that the various cortical areas form no such upwardly pointing pattern, either anatomical or conceptual. I believe that one could look upon the brain as what could rather be called a *lowerarchy*... An immediate reward would be that one is thereby relieved of deciding which part of the cerebral cortex is to be accorded primacy. That elusive top of the pyramid would be replaced by something rather more tangible: *the top of the spinal cord!*

Motor Orchestration Without a Conductor: A Concluding Metaphor

Imagine a world where there were tracks and trains, conductors and engineers, passengers and freight, etc., but no supervisors who surveyed the entire scene from a god-like perspective and issued commands. Would trains run off their tracks? Would passengers and freight be stranded? Would conductors and engineers become immobilized and indecisive? *No, not if the system had evolved without ever having required system-independent supervisory control in the first place!*

Alternatively, let us take any one structure within the motor system and categorically state: 'Here is where intentional, voluntary movement is initiated!' M1 is as good a candidate as any for this elevated status. As Zigmond *et al.* (1999, p. 931) remark, "While the motor cortex is not 'the whole story,' it is clearly the place to begin." However, to say that M1 initiates voluntary movement would be like saying a conductor *initiates* the train moving by signaling to the engineer. *Question: What set of prior internal or external events initiated the process of the conductor raising and signaling with the lantern?*

However, as suggested above, perhaps we have the story and therefore the question all wrong. We need to challenge the Cartesian assumption of an identifiable cause (namely, intentional, volitional states) sufficient to initiate the train of motor events issuing in the conductor's arm and lantern to be raised. It has been argued here that there simply is no identifiable cognitive nor neural event that, in and of itself, sets events in motion.

Rather, and as argued for in this paper, computations at different levels within motor nervous systems initiate, coordinate, modulate and sequence movements without Cartesian-like executives. Obviously, tracks, trains, engineers, and conductors break down from time to time, as do nervous systems. Disruptions in railroad schedules occur for the same reasons as do dysfunctions in motor systems: problems in signal transmissions between stations; broken or blocked tracks/tracts; equipment and system overload; and so on. It is not the *Will* or *Volition* or some other metaphysical agent/agency that breaks down here *but components within the system itself*, that is, within the system's physical or computational architectures (Farah & Feinberg, 2000; Heilman

& Valenstein, 1993; Mazzoni & Rowland, 2001; Simon *et al.*, 1999; Victor & Ropper, 2001).

References to a supervisor who initiates voluntary movements only invite an infinite regress of questions concerning what, in turn, initiates the supervisor's (or conductor's) choices. In the following passage, Flanagan's (1991, p. 43; see also his 2002) proposal is entirely consistent with the naturalistic model of *VMC* developed here. Concerning the *voluntary* in *VMC*, we must relinquish:

> the requirement that there must always be an outside comprehender or observer, and endow some part of, or the whole of, the brain...with reflexive powers, with the ability to loop around itself. If the only way to stop the infinite regress [of causal agents] is to allow the reflexivity we obviously possess at some point, then why not allow it a place in the cognitive system from the very start? This is precisely the direction in which a naturalist must move.

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