

Commentary/Plamondon & Alimi: Speed/accuracy trade-offs in target-directed movements

if a reader does not understand the main issue of the theory, the matter of formalization used is lost and any discussion is moot.

In conclusion, P&A write that their kinematic theory “encompasses both similarities and dissimilarities with respect to the other models previously published. . . . unlike . . . (Hogan 1984) . . . (Uno et al. 1989), . . . (Feldman 1966; 1986; Polit & Bizzi 1979) . . . [and] (Bullock & Grossberg 1988), . . . kinematic theory provides a global view. . . . The price to pay for such generalization is that it is difficult, without further experiments, to provide a direct biological interpretation for the system parameters . . .” (sect. 6, para. 4).

Unfortunately, the price for “such generalization” is higher. If a view is too global and generality is too high there is the risk of saying nothing about everything. P&A’s terminology is insufficiently accurate.

Neural models of reaching

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Abstract: Plamondon & Alimi (P&A) have unified much data on speed/accuracy trade-offs during reaching movements using a delta-lognormal form factor that describes “the asymptotic behavior of a large number of dependent linear systems,” notably neuromuscular systems. Their approach raises questions about whether a large number of systems is needed, whether they are linear, and whether the results disclose the neural design principles that control reaching behaviors. The authors admit that “it is difficult. . . to provide a direct biological interpretation for the system parameters” (sect. 6, para. 4).

The VITE model (Bullock & Grossberg 1988) of neural trajectory formation implies Fitts’ law, and various failures, as emergent properties of trajectory dynamics. VITE was derived to explain how motor *synergies* form, and how synergies contract *synchronously* at variable *speeds*. These three S’s (synergy, synchrony, speed) of reaching behavior imply Fitts’ law, as well as asymmetric velocity profiles and their invariances. They do so using a single, weakly nonlinear system rather than a large number of linear systems.

VITE multiplies a difference vector (*DV*), which codes the difference between desired target position and an outflow representation of present position – and a volitional GO signal. Are there other neural systems that use *DV*-style computations and that are cascaded together to provide multiple VITE-like contributions to Fitts’ law, none of which involves neuromuscular computations?

The VITEWRITE model (Bullock, Grossberg & Mannes 1993) embeds VITE into a movement-planning circuit for generating handwriting movements. The script letters are an emergent property of circuit interactions that enable writing to preserve its form as volitional acts flexibly change its size or speed. The script letters have an invariant representation as a spatial pattern of synergy-controlling *DVs* that are stored in a working memory. As in VITE, GO volitional signals can alter their speed of execution. GRO volitional signals alter their size by multiplying the *DV* that is read out of working memory; this product is then input to the VITE circuit. Feedback from VITE to working memory releases the next working-memory *DV* only when the VITE *DV* is maximal or zero. Complex data about stroke coordination, such as the “two-thirds power law” of Lacquaniti et al. (1983), arise as emergent properties of these feedback interactions. Nowhere does the circuit need the virtual targets or minimization principles that the authors mention.

DVs also occur during visually guided control of motor-equivalent reaching to targets in space. The direct model (Bullock, Grossberg & Guenther 1993) shows how accurate reaches can be made with novel tools of variable lengths, clamped joints, distortions of visual input by a prism, and unexpected perturba-

tions. The coordinate transformations from retinal, to head-centered, and finally to the body-centered coordinates that control reaches also use *DV* computations. Why are *DVs* so ubiquitous in the spatial planning and motor execution of reaches?

We propose that this is the correct computational format for autonomously learning the coordinate transformations and movement parameters that keep sensory-motor coordination accurate within a growing body (Grossberg et al. 1993; Guenther et al. 1994). P&A note that their approach “does not provide too many clues about the learning process itself.”

P&A say that VITE does not describe “the mechanical properties of the muscles.” This is because VITE concerns itself with outflow positional control. The FLETE model (Bullock & Grossberg 1991) links outflow VITE commands to spinal and cerebellar circuits that maintain positional accuracy of contracting muscles under variable tension. FLETE models identified spinal and motor components, such as Renshaw cells and gamma motoneurons, and simulated the multiple velocity peaks during ballistic movements (Bullock & Grossberg 1992) which P&A consider “one of the most powerful characteristics of” their model. VITE has since been extended to a model circuit for controlling reaching movements of variable speed and force in the presence of obstacles (Bullock et al. 1997). This model simulates the neurophysiological firing patterns of six identified cell types in cortical areas 4 and 5 during a wide variety of behavioral tasks.

P&A mention Weber law control of timed movements. A model of learning in the cerebellum describes how metabotropic glutamate receptors, acting at cerebellar Purkinje cell spines, may control adaptively timed learning that obeys a Weber law (Fiala et al. 1996).

In summary, whereas Plamondon & Alimi provide a stimulating account of how speed/accuracy data may arise from delta-lognormal processing, recent neural models of reaching behavior provide an alternative view of the design principles and nonlinear mechanisms whereby these data may arise as emergent properties.

Where in the world is the speed/accuracy trade-off?

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Abstract: Even though Plamondon’s kinematic model fits the data well, we do not share the view that it explains movements other than ballistic ones. The model does not account for closed-loop control, which is the more common type of movement in everyday life, nor does it account for recent data indicating interference with ongoing processing.

Plamondon & Alimi (P&A) state two specific goals. The first is to demonstrate the absence of a cohesive account for aimed movements; the second is to advance Plamondon’s kinematic theory as such an account. In general, P&A are successful with respect to these goals and are therefore to be congratulated. However, we have a number of questions, which principally concern real-world application of the findings, consistency with other data, and a potential weakness of the model itself.

It is our contention that P&A’s work only relates to a very small and generally atypical segment of the full spectrum of movement capability. Only under highly constrained and artificial conditions, such as in the experimental laboratory or at sporting events, does any individual regularly engage in ballistic movements occurring at or near their maximum movement velocity. Very few daily skills require performance at the levels of velocity and accuracy typical in the cited research (although an obvious exception is keyboard-

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ing). P&A are appropriately prudent about claims of improved curve fitting of the order of 1% to 2%. However, the form of behavior at hand represents perhaps 1% to 2% of the range of potential movement capabilities and the limit on generality is therefore indeed a critical one.

P&A refer to these movement as well-learned. Relatively, they are not. If any one individual research participant engaged in more than perhaps two hundred such movements it would be unusual. Compare this to the millions of repetitions at lower velocities for such actions as reach and grasp. Of course, P&A can protest that the latter movements are accounted for by their model, but there is a further objection to be raised: one hallmark of skill is energy minimization. Given this, high-level skills may well be composed of a single agonist burst, in which the constraints of the environment and/or the object/tool at hand could perform the antagonistic function. Where does this leave a model that depends crucially upon the interplay of signals from both agonist *and* antagonistic muscles to achieve the desired outcome? The absence of a D_2 signal in this situation only further delimits the task domain explained by the kinematic model.

Also, what is the nature of the outcome being accounted for? In certain conditions it is absolute error (AE), but AE is a derivative of the first two distributional moments and reflects neither in a pristine condition. Although P&A are right to focus on the relative accuracy of movement, they limit themselves to a combinatorial reflection that itself can be problematic (Newell & Hancock 1984; Schutz & Roy 1973). Besides, error in the sense of an obvious, gross mistake, rather than merely a close miss, also seems to be beyond the direct purview of the present approach.

P&A ignore various clear indications that slower aiming movements especially rely on closed-loop control in a limited capacity system. Many studies indicate the use of visual feedback and the existence of interference from concurrently performed tasks in aiming tasks. P&A do mention the possibility that deviations from the $\Delta\Delta$ law might be explained by the use of continuous feedback in some aiming movements. However, they overemphasize the applicability of the Plamondon model in an attempt to show that it can do what all other models could not: explain the data. In line with this contention, P&A's ideas of sequence control in section 5.5 do fit current notions obtained in reaction time studies (e.g., Verwey 1996). However, those studies also show slowing effects of higher level processing on movement execution. Such data cannot be accounted for by Plamondon's kinematic theory, which basically rejects any form of on-line control.

A clear weakness of the model itself is that in section 4.5 P&A suddenly introduce the possibility that, besides D_1 and D_2 , the *system* parameters μ_1 , μ_2 , σ_1 , and σ_2 are programmable also. Apart from the biological implausibility of changing these parameters, adding the modifiability of these parameters as well would provide the model with sufficient degrees of freedom to explain virtually any movement outcome.

Finally, P&A are obviously enthusiastic proponents of the mathematical form of description. Indeed, they consider only explanatory constructs that use this notation. For example, they conclude, "None of the theoretical explanations proposed to date is able to take into account the major experimental observations in the field under a single scheme" (sect. 3, para. 1). This statement is true if only mathematical descriptions are considered. However, we would claim that the descriptive theoretical structure proposed by Hancock and Newell (1985) over a decade ago provides such an initial description and indicates the sequence of connections that must occur between intention, muscular activation, kinetic and kinematic descriptions, and related subsequent outcome. What was also avoided in the latter work was spurious theorizing about causation, relying upon underdeveloped constructs such as "noise" to redescribe the phenomena in different terms. It is unfortunate therefore, that P&A relapse into this "explanation" at a critical juncture of their work.

While we have focused upon some issues of concern, our comments should not be taken as overly critical. In general, the

work is soundly conceived and presents new insights to the problem. It is in consequence a good step forward in understanding the intrinsic problems of movement control, and we applaud the effort.

Neuronal and muscular correlates consistent with Plamondon's theory: Velocity coding and temporal activation patterns

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Abstract: This commentary cites several findings of neuromuscular research that are consistent with aspects of Plamondon's kinematic theory. In addition, we point out certain biomechanical properties of the limb that influence the requirements for the production of accurate movement, and might thus compromise the global applicability of any law governing speed/accuracy trade-offs.

Plamondon & Alimi's (P&A's) idea that velocity is one of the main control parameters in the production of movements is consistent with several findings in neuromotor control research. In a study by Georgopoulos and colleagues (1992), the motor cortical population vector was found to be related to the change in force rather than to the force exerted by the subject, suggesting that cortical neurons are concerned with phasic commands. At the level of force output, Hollerbach and Flash (1982) have identified two distinct components of joint torque: a "gravity" torque with an invariant contribution to movements of different speeds, and a "drive" torque, scaling quadratically with linear changes in velocity. Accordingly, Flanders and Herrmann (1992) found two independent elements of muscle activation, whose weighted sum could account for the EMG signals observed during arm movements of different speed. While one "tonic" component had a constant weighting coefficient at all speeds, the other "phasic" component's coefficient scaled monotonically with velocity. The "drive" torque, or, concurrently, the "phasic" EMG component, could thus be interpreted as the result of a motor command concerned primarily with the control of velocity.

Similarly, certain temporal aspects of muscular activity patterns are consistent with P&A's notion that the delay time, with which a muscle is activated, depends on whether the muscle acts as an agonist or antagonist in the movement: Flanders and colleagues (1996) showed that the timing of the phasic EMG activity of human arm muscles during reaching gradually changed as a function of movement direction, from an early burst for the agonist direction to a later burst for the antagonist direction. This pattern of temporal shifting with direction persisted under dynamic isometric conditions, where it did not represent the mechanically optimal solution (Pellegrini & Flanders 1996). These robust features of muscle activation could thus be the result of a central neuromuscular control strategy like the one proposed in the target article.

Any theory attempting to explain the ubiquitous phenomenon of speed/accuracy trade-offs with a global law governing neurally generated movements will eventually have to be tested under broader conditions than those involved in the standard Fitts' task. More specifically, the law will have to deal with the nonuniform biomechanical requirements for multijoint movements in different directions and different parts of the workspace that arise from the pattern of the limb's elastic and inertial anisotropy (see Mussa-Ivaldi et al. 1985). In fact, Gordon and Ghez (1987) showed that for arm movements in different directions, subjects scaled their movement times in order to compensate for the differences in initial acceleration arising from the limb's inertial anisotropy. Soechting et al. (1995) found that for pointing movements, the arm's final posture depended on its initial posture in a way best