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Speed-accuracy trade-off in planned arm movements with delayed feedback

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Abstract

The Vector Integration to Endpoint (VITE) circuit describes a real-time neural network model simulating behavioral and neurobiological properties of planned arm and hand movements by the interaction of two populations of neurons. We analyze the speed-accuracy trade-off generated by this circuit, generalized to include delayed feedback. With delay, two important new properties of the circuit emerge: a breakdown of Fitts' law when the movement time is small relative to the delay; and a positive Fitts' law *Y*-intercept. This breakdown of Fitts' law for tasks with small Index of Difficulty has been previously observed experimentally, and we suggest it may be attributed at least in part to delay effects in the nervous system elaborated by the model. Additionally, this gives a theoretical explanation for why positive Fitts' law *Y*-intercept should occur, and that it is related to the delay within the movement circuit.

Keywords: Fitts' Law; Sensory-motor control; Information theory; Delay differential equations; Hand–eye coordination; Arm movement; Neurodynamics

1. Introduction

The Vector Integration To Endpoint (VITE) circuit (Bullock & Grossberg, 1988) describes a real-time neural network model simulating behavioral and neurobiological properties of planned arm movements (Bullock & Grossberg, 1992). Unlike other models of motor control, the VITE model does not rely on explicit trajectories or kinematic invariants represented within the model. Instead, the movements generated by the VITE circuit emerge from the dynamical interaction of network variables. Quantitative simulations of the model provide results consistent with data pertaining to numerous kinematic properties, including the speed-accuracy trade-off of movements (Fitts' law (Fitts, 1954, 1964) and Woodworth's law (Woodworth, 1899)), isotonic arm movement properties, 'error-correcting' properties of isotonic contractions, velocity amplification during target switching, velocity profile invariance and asymmetry, changes of velocity profile at higher speeds, automatic compensation of staggered onset times for synergetic muscles, the inverse relationship between movement duration and peak velocity, and peak acceleration as a function of movement amplitude and duration (Bullock & Grossberg, 1988).

There are four variables in the VITE circuit. Two of these are under active control of the subject: the Target Position Command (TPC) which represents the final desired position of the arm upon completion of the movement; the GO signal (GO) which specifies the overall speed of movement as well as the will to move at all. The two remaining variables are under automatic control as part of a feedback loop: the Present Position Command (PPC) is an internal representation of the location of the arm, and the Difference Vector (DV) is the difference between the TPC and PPC at any given time.

The synthesis of a movement trajectory involves the interaction of the above-defined variables. The actual outflow commands, which act on the arm muscles to cause contraction, and consequently arm movement, are generated by the PPC. Each outflow command moves the arm toward the position coded for by the PPC. In order to produce a continuous movement, there must be a succession of PPCs. Only one constant TPC, which remains active

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during the entire movement, is required to generate the appropriate trajectory.

The continuous computation of new PPCs relies on the continuous computation of DVs. The DV, which encodes the difference between the fixed TPC and the constantly changing PPC, indicates the direction and amplitude required to complete the movement. Difference vectors are calculated in the motor cortex by a specific population of vector cells that are sensitive to a broad range of directions (Leonard, 1998). The DV is actually computed by subtracting the PPC from the TPC. The PPC will equal the TPC only when the DV is equal to zero. As a result, the DV gets smaller and smaller as the arm approaches the target position. The updating process that occurs between the PPC and the DV is a negative feedback loop whereby the DV is constantly reduced by the movement of the PPC towards the TPC. Thus, the PPC is a cumulative record of all past DVs which were responsible for bringing the PPC towards the TPC (i.e. the PPC integrates all past DVs). It must be noted here that since we have two separate groups of neurons interacting, the PPC activity may have reached the target while the DV has not yet reached a value of zero. Physically, this situation manifests itself as an overshoot of the target, or movement error.

The GO signal exists in between the PPC and the DV and acts as a multiplier for the circuit. It embodies the concept of volition to planned arm movement velocity (Bullock & Grossberg, 1989). A larger GO signal will result in a faster movement and a smaller GO signal will result in a slower movement. The GO signal is also responsible for stopping movement before a trajectory is complete. This is an important property of arm movements that are determined to be dangerous before completion.

The VITE network proposed in Bullock and Grossberg (1988) is a system of non-linear differential equations

$$\frac{dV}{dt} = \alpha[-V(t) + T(t) - P(t)], \quad (1)$$

$$\frac{dP}{dt} = G(t)[V(t)]^+, \quad (2)$$

where $V(t)$ is the activity of the agonist's DV population, $P(t)$ is the activity of the agonist's PPC population, $G(t)$ is the GO signal, $T(t)$ is the target position input and:

$$[V(t)]^+ = \begin{cases} V(t), & \text{if } V(t) \geq 0, \\ 0, & \text{if } V(t) < 0. \end{cases} \quad (3)$$

While the choice of constant GO function $G(t) = G$ allows tractable analysis of the above system, it is more realistic to consider a GO function of the form $G(t) = G_0 g(t)$, where $g(t)$ is a monotonically increasing function (not necessarily continuous). The function $g(t)$ is called the *GO onset function*, and describes the transient buildup of the GO signal after it is switched on. The constant G_0 is called the *GO amplitude* and parameterizes how large the GO signal can become.

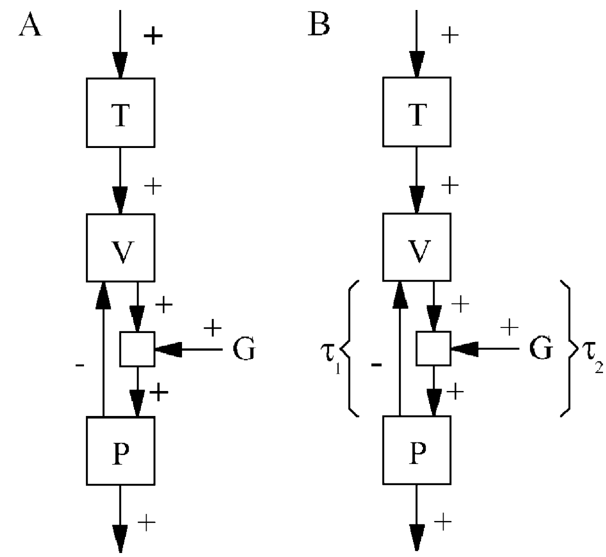

Fig. 1. (A) The VITE circuit involving $V(t)$: the activity of the agonist's DV population, $P(t)$: the activity of the agonist's PPC population, $G(t)$: the GO signal and $T(t)$: the target position. (B) The VITE circuit with delay between the two populations of neurons: τ_1 and τ_2 represent the signal delay from the PPC population to the DV population, and from the DV population back to the PPC population, respectively.

Bullock and Grossberg (1988) considers GO onset functions of the form

$$g(t) = \begin{cases} \dfrac{t^n}{\beta^n + \gamma t^n}, & \text{if } t \geq 0, \\ 0, & \text{if } t < 0, \end{cases} \quad (4)$$

where β, $\gamma = 1$ or 0 to generate PPC profiles through time which are in quantitative accord with experimental data. Specifically, if $\beta = 1$ and $\gamma = 0$, then $g(t)$ is a linear function of time if $n = 1$ and faster-than-linear when $n > 1$, and if $\beta = 1$, $\gamma = 1$, and $n = 1$ then $g(t)$ is slower-than-linear.

See Fig. 1A, which contains a schematic diagram of the VITE circuit

2. VITE model with delayed feedback

The VITE model is a negative feedback model whereby two groups of interacting neurons participate in a continuous updating process. It is natural to introduce time delay into this neural network because of the characteristic of neurons to behave as delay lines (Pauvert, Pierot-Deseilligny, & Rothwell, 1998; Ugawa, Genba-Shimizu, & Kanazawa, 1995). As well, neurons which interact in a negative feedback manner can often have longer associated delays than neurons which do not (Shepherd, 1998). The vector cell populations discussed in Bullock and Grossberg (1988) are located in the cerebral cortex which was once thought to contain cells which had a very fast response time to synaptic input but has recently been given a moderate value of