1993-01

The VITEWRITE Model of Handwriting Production

https://hdl.handle.net/2144/1988

THE VITEWRITE MODEL OF HANDWRITING PRODUCTION

Daniel Bullock, Stephen Grossberg, and Christian Mannes

January 1993

Technical Report CAS/CNS-93-011

Boston University Center for Adaptive Systems and
Department of Cognitive and Neural Systems
111 Cummington Street
Boston, MA 02215

THE VITEWRITE MODEL OF HANDWRITING PRODUCTION

Daniel Bullock*, Stephen Grossberg†, Christian Mannes‡

Center for Adaptive Systems and Department of Cognitive and Neural Systems
Boston University, 111 Cummington Street, Boston, MA 02215

Abstract

This article describes the VITEWRITE model for generating handwriting movements. The model consists of a sequential controller, or motor program, that interacts with a trajectory generator to move a hand with redundant degrees of freedom. The neural trajectory generator is the Vector Integration to Endpoint (VITE) model for synchronous variable-speed control of multijoint movements. VITE properties enable a simple control strategy to generate complex handwritten script if the hand model contains redundant degrees of freedom. The controller launches transient directional commands to independent hand synergies at times when the hand begins to move, or when a velocity peak in the outflow command to a given synergy occurs. The VITE model translates these temporally disjoint synergy commands into smooth curvilinear trajectories among temporally overlapping synergetic movements. Each synergy exhibits a unimodal velocity profile during any stroke, generates letters that are invariant under speed and size rescaling, and enables effortless connection of letter shapes into words. Speed and size rescaling are achieved by scalar GO and GRO signals that express computationally simple volitional commands. Psychophysical data such as the isochrony principle, asymmetric velocity profiles, and the two-thirds power law relating movement curvature and velocity arise as emergent properties of model interactions.

1. Introduction

Skilled handwriting generally involves the coordinated action of a large number of joints, from the shoulder down to the joints of the fingers, each of which must be controlled by the muscle groups attached to them. This paper addresses how the kinematics of these joints may be controlled to produce the shapes of cursive script. A great deal of research has been devoted to explaining the kinematic signatures of point-to-point movements during reaching. The Vector Integration To Endpoint (VITE) model (Bullock and Grossberg, 1988, 1991), upon which the VITEWRITE model is based, has successfully analysed synchronous multi-joint reaching movements at variable speeds. However, handwriting goes far beyond simple point-to-point movement, in that it requires control of the trajectory at any point. The smooth, curved trajectories of a pen tip in cursive script are not simple point-to-point movements, but rather express a motor plan that schedules the time course of action of the many components of arm and hand. Analyzing the geometry of a hand, one finds that no mere concatenation of point-to-point movements can produce the complex shapes of script. Rather, such trajectories appear to be generated by component actions that overlap in time (Morasso 1981, 1986; Plamondon, 1989; Schomaker, Thomassen, and Teulings, 1989).

Our approach to generating curved trajectories exploits the the fact that the hand has more than two degrees of freedom. Trajectories that require precisely scheduled onsets and offsets of components in a two degrees of freedom system can be generated by a three degrees of freedom system with only two possible phase relations between component onsets, and no rescaling of component velocity profile durations. Other advantages of the model include dramatically compressed motor codes, a simple sequential launching mechanism that does not require storage of within-stroke time lags, and effortless concatenation of letter trajectories. The model also retains desirable properties of the VITE model, including the isochrony principle (Schomaker, Thomassen, and Teulings, 1989; Viviani and Terzuolo, 1983), or the tendency for strokes of different size to be completed with approximately equal duration; skewed velocity profiles (Wann, Nimmo-Smith, and Wing, 1988), typically with faster rise and slower fall in velocity; the synthesis of continuous complex movements from unit segments (Soechting

---

[*] Supported in part by the Office of Naval Research (ONR N00014-92-J-1309) and the National Science Foundation (NSF IRI 90-24877 and NSF IRI 87-16960).

[†] Supported in part by Air Force Office of Scientific Research (AFOSR F49620-92-J-0225), DARPA (AFOSR 90-0083), the National Science Foundation (NSF IRI 90-24877 and NSF IRI 87-16960), and the Office of Naval Research (ONR N00014-92-J-1309).

[‡] Supported in part by the National Science Foundation (NSF IRI 90-24877).

and Terzuolo, 1987); and the tendency of maximal curvatures of a trajectory to occur at locations of minimum velocity (Abend, Bizzi, and Morasso, 1982; Fetters and Todd, 1987; Viviani and Terzuolo, 1980).

2. Model Heuristics

There are three main aspects of our model: a geometrical model of the hand, a VITE neural trajectory generator, and a controller to launch motor codes sequentially, such that curved spatiotemporal trajectories can unfold. Our hand model has three degrees of freedom (DOFs): vertical wrist rotation (supination/pronation, called X) finger extension/retraction (called Y), and horizontal wrist rotation (called R), as in Figure 1.

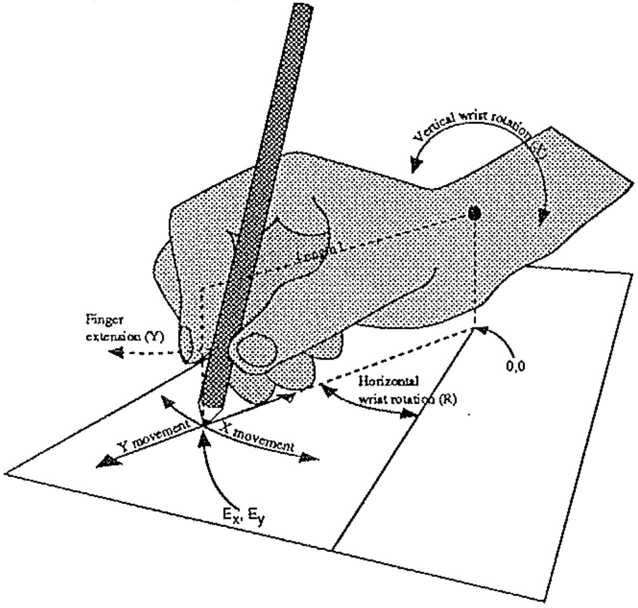


Figure 1: The geometric model of the hand to be controlled, with three degrees of freedom: finger extension/retraction, which moves the pen along the up-down (Y) axis, vertical wrist rotation (supination/pronation), which has the effect of moving the pen along the left-right (X) axis, and horizontal wrist rotation (R), which has two effects: rotating the other two axes, and moving the pen left-right.

Under the assumption that both the effects of finger extension and vertical wrist rotation are small in relation to the total range, both X (vertical wrist rotation) and Y (finger extension) can be modeled as an orthogonal system of spatially straight lines. If the wrist is located at spatial location (0,0), then the pen tip, or end effector location (E_x, E_y) can be found by

$$E_x = (l + y)\sin(r) + x\cos(r) \qquad \text{and} \qquad E_y = (l + y)\cos(r) - x\sin(r) \tag{1}$$

where x and y denote the X and Y excursions, respectively, and r stands for the horizontal angle of the hand with respect to the arm. The length of the hand from the wrist to the knuckles, denoted as l, is large relative to the X, Y and R excursions.

The Vector Integration To Endpoint (VITE) model of Bullock and Grossberg (1988, 1991) is a neural model of how the outflow commands that control multi-joint motor trajectories are formed. In particular, the model clarifies the intimate linkage that exists between movement properties of synergy, synchrony, and speed. It shows how a group of effectors may be dynamically bound into a motor synergy, and once bound, how the synergy can perform synchronous movements at variable speeds.

The VITE circuit consists of four neural stages: The first stage, the Target Position Vector (TPV) stage receives desired positions coded in terms of muscle lengths from higher stages. The Present Position Vector (PPV) stage generates outflow movement signals to spinal neuron pools, which in turn act on muscles capable of moving the arm. The Difference Vector (DV) stage continuously computes the difference between PPV and TPV using excitatory outflow signals from the TPV and inhibitory corollary discharge, or efference copy, signals from the PPV. Outflow from the DV to PPV is multiplied, or gated, by a nonspecific GO signal. Before any movement begins, a desired position command may be loaded into the TPV and relayed to the DV. Until the GO signal grows positive, however, no change in PPC can occur. Once the GO signal becomes positive, the PPV can start integrating signals at the rate GO·DV. This multiplicative interaction maintains the direction coded by DV while modulating the speed of movement in this direction. Since the PPV integrates DV·GO, the rate of change of the outflow PPV signal, namely $\frac{d}{dt}$PPV, tracks DV·GO. Thus DV·GO provides an internal measure of the commanded movement velocity that is used to launch sequential motor commands. The DV is driven to zero by inhibitory feedback from PPV to DV as the PPV approaches the TPV. The system thus equilibrates when the PPV equals the TPV.

The production of curved trajectories during handwriting requires that distinct movement components have distinct but overlapping velocity profiles. Correspondingly, the three synergies of our hand model are controlled by their own VITE circuits, with separately initiated GO signals. A mechanism is also needed to reset these GO signals before the onset of a new movement by each synergy.

3. Model Equations

The equations that govern VITEWRITE dynamics are now described. The TPV is denoted by $T = (T_1, T_2, \ldots, T_n)$, the PPV by $P = (P_1, P_2, \ldots, P_n)$, the DV by $V = (V_1, V_2, \ldots, V_n)$ and the GO signal by $G = (G_1, G_2, \ldots, G_n)$, where index i denotes the ith motor synergy.

Target Position Vector: $$T_i(t_{i,j+1}) = D_i(t_{ij}) + T_i(t_{ij}) \tag{2}$$

The TPV is input to the system from higher processing stages. Targets $D_i(t_{ij})$, the components of the motor programs, are directional commands, such that at launch times $t_{ij}, j = 1, \ldots, n$, the new directional target $D_i(t_{ij})$ is added to the TPV.

Difference Vector: $$\frac{d}{dt}V_i = \alpha(-V_i + T_i - P_i) \tag{3}$$

where P_i is the i-th component of the PPV.

GO Signal: $$G_i(t) = G_0(t - t_{ij})^n \qquad t_{ij} \leq t < t_{i,j+1}, j = 1, \ldots, n \tag{4}$$

where G_0 is a constant and t_{ij} is the point in time at which component i is launched. At that time, the GO signal is reset to zero and grows monotonically until $t_{i,j+1}$, at which time the next movement is launched. This stereotyped and repetitive GO signal rule is capable of generating arbitrary cursive script letters. In our simulations, we used $n = 1.4$.

Present Position Vector: $$\frac{d}{dt}P_i = V_i G_i \tag{5}$$

The PPV integrates its input signals at the rate $V_i G_i$.

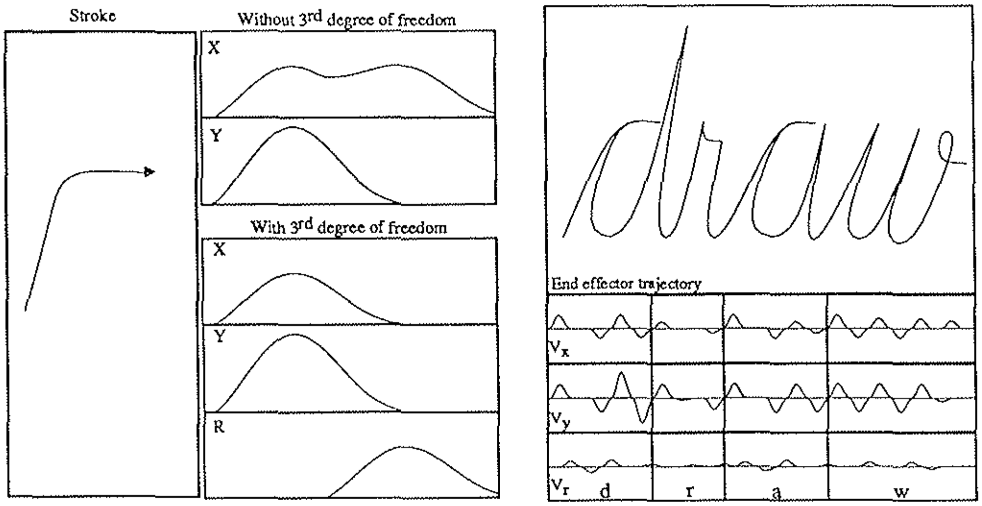
4. An Activity-Dependent Motor Program

To produce the smooth, curved trajectories of script, synergy TPV directions and GO signal onsets need to be appropriately timed. The directions and onset lags of different synergies determine script curvature. Furthermore, in order to generate a letter shape, elementary strokes need to be joined together smoothly. Our simulations show that two events are suitable to launch a stroke: Times when all velocities are close to zero, and times at the peak of one or more velocity traces. These two types of events are called a *postural launch* (detected by a match between TPV and PPV) and a *dynamic launch* (detected by a peak in one or more velocity profiles).

Each peak and zero in the velocity trace can activate read-in of a new movement command containing directional TPV targets for each component. Such a non-zero target signal is also used to reset the GO signal of that component. The TPV commands point in the independent X, Y, and R directions. Their amplitudes were chosen equal to the maximal excursion of the letter in that direction. The order and timing of these synergy commands determine the curvature of the movement. All the stored commands in the "motor program" that characterizes a letter in this scheme are generated at discrete times in independent directions. The VITE model converts these discrete commands into continuously curved trajectories of appropriate shape. Such a controller affords a huge compression of the commands needed to generate cursive script.

5. Simulations of Cursive Script and Elements of Style

Figure 2a exemplifies how the use of a third degree of freedom can simplify neural control: Using two degrees of freedom, the stroke shown in Figure 2a can only be generated using a mix of unimodal and bimodal velocity profiles with unequal component movement durations. By adding a third degree of freedom, R, that acts much like X, the stroke can be generated using unimodal, bell-shaped velocity profiles with equal durations. This redundant degree of freedom thus reduces the controlller complexity. Redundancy also allows letters to be produced in different ways. For example, consider the beginning right-upward stroke of most letters (Figure 2b). This stroke can be achieved by X to the right, Y up, R right; R right, Y up, X right; or R right, X and Y in phase obliquely up, followed by R right.



(a) (b)

Figure 2. (a) A stroke that is greatly simplified by use of a third degree of freedom. Left: With two degrees of freedom, a stroke as shown in the middle can only be obtained by a mix of bimodal and unimodal velocity profiles, since the horizontal component is non-zero before and after the bend. Right: Using a third degree of freedom (R), which acts much like X, allows production of the same shape with only unimodal velocity profiles. (b) Connecting letters by concatenating individual motor programs.

Redundancy thus allows for similar shapes to be realized by different motor programs. The need to connect letters into words exploits this flexibility by the use of a consistent style. Such a consistent style enables the size and slant of letter shapes to be altered simply by scaling the elements of the motor program differentially, as in Figure 3.

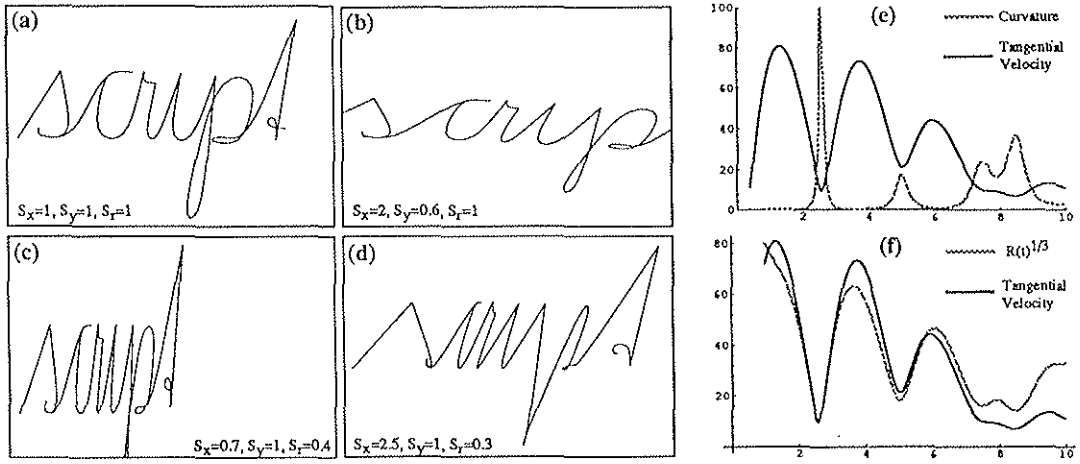


Figure 3. (a)-(d): Effect of scaling component targets: An unscaled version of a word composed by concatenating letter programs. The same word written with all X targets multiplied by $S_x = 2$, Y targets by $S_y = 0.6$ (b). Another version with $S_x = 0.7, S_y = 1, S_r = 0.4$ (c), and with $S_x = 2.5, S_y = 1, S_r = 0.3$. (e)-(f): Relationship between pen tip (tangential) velocity $V(t)$ and curvature for a letter "b." Plot (e) plots curvature and velocity, which show the expected inverse relationship. Plot (f) compares $V(t)$ with $kR(t)^{1/3}, k = 10$; see text.

6. Size, Speed, Slant, and Curvature Invariance

The kinematics of handwriting trajectories are invariant with respect to variations in starting point, slant, and size (Viviani and Terzuolo, 1980; Morasso 1981). These invariances are also exhibited by the model: Figure 3a-d displays variations of a trajectory achieved by differentially scaling—i.e. multiplying each component TPV_i by a different scalar S_i—the elements of the motor program. While the results look different, the velocity profile is the same except for relative magnitude. Multiplying each component TPV_i by the same scalar S (a GRO signal) modifies the *size* of the letters, but leaves the *shape* invariant.

Another widely observed invariant of movement is the strong coupling between velocity and curvature. Lacquaniti, Viviani, and Terzuolo (1983) formulated a "two-thirds power law": angular velocity $A(t)$ relates to curvature $C(t)$ as $A(t) = kC(t)^{2/3}$, which for tangential velocity $V(t)$ becomes $V(t) = kR(t)^{1/3}$, where $R(t) = 1/C(t)$ denotes the radius of curvature. Figure 3e plots model curvature and model tangential velocity for the letter "b"; Figure 3f plots model tangential velocity alongside the tangential velocity predicted from model curvature by the two-thirds power law. The agreement is close but not perfect, as observed by Wann, Nimmo-Smith, and Wang (1988), because human velocity profiles are not perfectly symmetrical about the peak velocity value (Bullock and Grossberg, 1988, 1991; Nagasaki, 1989), as is also true of VITE.

References

Abend, W., Bizzi, E., and Morasso, P. (1982). Human arm trajectory formation. *Brain*, **105**, 331–348.

Bullock, D. and Grossberg, S. (1988). Neural dynamics of planned arm movements: Emergent invariants and speed-accuracy properties during trajectory formation. *Psychological Review*, **95**, 49–90.

Bullock, D. and Grossberg, S. (1991). Adaptive neural networks for control of movment trajectories invariant under speed and force rescaling. *Human Movement Science*, **10**, 3–53.

Fetters, L. and Todd, J. (1987). Quantitative assessment of infant reaching movements. *Journal of Motor Behavior*, **19**, 147–166.

Lacquaniti F., Terzuolo C., Viviani P., (1983) The law relating the kinematic and figural aspects of drawing movements. *Acta Psychologica* **54**, 115-130.

Morasso, P. (1981). Spatial control of arm movements. *Experimental Brain Research*, **42**, 223–227.

Morasso, P. (1986). Trajectory Formation. In P. Morasso and V. Tagliasco (Eds.), **Human Movement Understanding.** Amsterdam: North-Holland.

Nagasaki, H. (1989). Asymmetric velocity profiles and acceleration profiles of human arm movements. *Experimental Brain Research*, **74**, 319–326.

Plamondon, R. (1989). Handwriting control: A functional model. In R.M.J. Cotterill (Ed.), **Models of brain function.** Cambridge: University Press.

Schomaker, L., Thomassen, A., and Teulings, H.L. (1989). A computational model of cursive handwriting. In R. Plamondon, C.Y. Suen, and M.L. Simner (Eds.), **Computer Recognition and Human Production of Handwriting.** Singapore: World Scientific, 153–177.

Soechting, J.F. and Terzuolo, C.A. (1987). Organization of arm movements is segmented. *Neuroscience*, **23**(1), 39–51.

Viviani, P. and Terzuolo, C.A. (1980). Space-time invariance in learned motor skills. In G.E. Stelmach and J. Requin (Eds.), **Tutorials in motor behaviour**, Amsterdam: North-Holland, 525–533.

Viviani, P. and Terzuolo, C.A. (1983). The organization of movement in handwriting and typing. In B. Butterworth (Ed.), **Language production.**, **2**. New York: Academic Press, 103–146.

Wann, J., Nimmo-Smith, I., and Wing, A.M. (1988). Relation between velocity and curvature in movement: Equivalence and divergence between a power law and a minimum-jerk model. *Journal of Experimental Psychology: Human Perception and Performance*, **14**(4), 622–637.