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Generalized Motor Programs: Reexamining Claims of Effector Independence in Writing

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ABSTRACT

This chapter reports detailed analyses of writing data designed to provide a clearer idea of the generality and limits of effector independence in writing. Confirming previous observations of overall shape similarity across effectors, these analyses also reveal systematic changes in details of shape, kinematics, stroke decomposition, and fluency occurring with changes in effector. These results serve as the basis for reconsidering the implications of empirical effector independence in writing for the hypothesis that motor programs can be generalized to operate across effectors. Although strong assertions are premature, the results reported are consistent with the conclusion that writing by the dominant and the nondominant hands is carried out using different strategies that share only the very highest and most abstract spatial representations of what the shape of the writing should be. By contrast, writing with the dominant hand and the dominant arm appears to be controlled by mechanisms that share a common representation much lower in the hierarchy of increasing motor specificity particularly for highly overlearned productions such as one's name.

INTRODUCTION

Background

In the last 20 years, the nature of cognitive representations used to plan and carry out movements and movement sequences has been a major focus

of research on movement control (e.g., Gentner, 1983; Keele, 1981; Kelso, 1977; Meyer, Smith, & Wright, 1982; Meyer, Abrahms, Kornblum, Wright, & Smith, 1988; Rosenbaum, 1980; Rumelhart & Norman, 1982; Saltzman & Kelso, 1987; Schmidt, 1975; Schmidt, Zelaznik, Hawkins, Frank, & Quinn, 1979; Sternberg, Monsell, Knoll, & Wright 1978). The concept of the *motor program* has played a key theoretical role in this work. Although its role has remained central, the concept itself has hardly remained static throughout this period.

In their early usage of the term, authors such as Henry and Rogers (1960), Keele (1968), and Adams (1971), for example, conceived of a motor program as a movement-specific, temporally structured collection of parameter values—that is, force, velocity, duration, muscle sequencing—that, when transmitted directly to the motor system, would initiate and carry through a specific action. This conception was proposed largely to explain the development of coordination, as skill in complex movements increases. In less skilled performance we usually observe corrective processes operating: The performer makes part of the overall movement (hereafter, a *submovement*), evaluates the result, makes another submovement, reevaluates, and so on. The result is jerky, temporally unstructured, and depends heavily on concurrent visual feedback (Pew, 1966). In skilled movements, the submovements are coordinated with one another and seem to anticipate or coincide with the events in the environment. Because the time between submovements, in a skilled movement, is often less than estimates of the time it takes to process feedback and initiate new commands, a reasonable inference is that the submovements making up the full movement have been stored in a memory structure so that they can be sequenced and executed without stimulus–response chaining or extensive feedback processing. (See Keele & Summers, 1976, for an excellent review of the evidence for and against this inference.)

More recently, a motor program has come to be thought of as a collection of generalized instructions representing not one, but a class of related movements. Before being transmitted to the muscles, these generalized motor programs must undergo a transformation: Variables contained in the generalized instructions, which allow delayed specification of at least some movement parameters, are replaced by specific values appropriate for the particular movement to be made. Bernstein (1967; but more usefully see Whiting, 1984) is probably the most influential early contributor to these ideas. The article of Schmidt (1975) had a major contemporary role in popularizing this conception among psychologists, which has been adopted and elaborated by others (e.g., Raibert, 1977; Schmidt, et al., 1979; Rosenbaum, 1980; Viviani & Terzuolo, 1980; Rosenbaum & Kornblum, 1982; Meyer, et al., 1982; Stelmach, Mullins, & Teulings, 1984; Meyer, et al., 1988).

One strong appeal of the generalized motor program hypothesis is the explanation it provides for how we produce novel variants of previously learned movements. By this hypothesis, the novelty problem is solved simply by changing the value of variables in the program. If we are limited to specific motor programs, however, we must use trial and error to create a new program for each new element in a class of "similar" movements. Empirically, the challenge posed by these alternatives is to establish criteria that can distinguish the direct transfer of learning, made possible by the existence of a generalized motor program, from the presumably slower process of generating new, specific motor programs (while perhaps benefiting from the information contained in the previously existing instances). Theoretically, the challenge of the generalized motor program hypothesis is to create models of the computations necessary for generalization of particular movement parameters that are consistent with other known regularities of motor performance.

Effector-Independent, Generalized Motor Programs

Within this framework, I focus on the specific claim, made by some as part of the generalized motor program hypothesis, that motor programs can be *effector independent* (e.g., Schmidt, 1975, 1988; Raibert, 1977; Rosenbaum, 1980; Stelmach, et al., 1984). In the broadest interpretation of this claim, an effector-independent, generalized motor program, once established for a particular movement, can be used to control performance of that movement by any of a number of muscle–joint systems (*effectors*) in the body, although perhaps with some loss of precision. This claim evolves from the idea that specification of particular muscles and joints is not a necessary part of a motor program, but rather, as with other aspects of generalized motor programs such as amplitude and timing, the choice of effector may be represented by variables that are replaced by specific values only at the time of the movement. Considering the radically different geometries of the various muscle–joint systems in the body, this claim, at least in its most radical form, is quite extraordinary.

Take, as an example, the joints and activating muscles used for movements made with a combination of fingers and the wrist. This muscle–joint system differs radically in geometry and in the implementation of degrees of freedom from the combination of the elbow and shoulder often used for similar movements on a larger scale. These differences in muscle–joint organization are so large that it is hard to see how detailed, low-level plans for movements made by one of these combinations could be easily transformed so that they could be used to control the same movement with the other combination. And yet, the finger–wrist combination is used for normal handwriting, whereas the elbow–shoulder combination is primarily responsible for larger writing, such as on a blackboard, two related activities often suggested as candidates for control by a single, effector-independent motor program.

It is difficult for me to reconcile the two conceptions of the motor program. On the one hand, there is the idea of a motor program as a repository for the information, presumably fairly detailed and low level, acquired as skill is developed. On the other hand, there is the conception, implicit in the effector-independence hypothesis, of a representation containing no specific information about muscles and joints. My dilemma centers on how the information necessary to support skilled performance with particular effectors is stored in or integrated with the abstract information in an effector-independent representation.

Effector Independence in Writing

Most authors when considering effector independence (e.g., Keele, 1981; Schmidt, 1988; Stelmach, et al., 1984) cite two sources for empirical support, Merton (1972) and Raibert (1977). Both of these works display samples of a phrase written with different muscle–joint effector systems. Merton (1972) compared an example produced by the fingers and wrist of the dominant hand with an example, roughly ten times larger, produced by the elbow and shoulder of the dominant limb. Raibert's (1977) palindromic demonstration compared one sample of the phrase "Able was I ere I saw Elba" produced by each of the dominant hand, the dominant arm with the wrist immobilized, the nondominant hand, the head with the pen gripped in the teeth, and the leg with the pen taped to the foot. Both Merton (1972) and Raibert (1977) emphasize striking similarities of shape between performances with different effectors.

So far as it exists, this evidence of effector independence in writing is unambiguous. My concern is with the fact that these demonstrations do little to establish the limits of this phenomenon. If this empirical similarity is interpreted only as evidence for *some* common underlying representation across effectors, then there is little problem. But, in most cases, the empirical observations are interpreted more strongly, as specific evidence that the underlying representations are effector-independent, generalized motor programs. The evaluation of this claim requires both that the claim be elaborated more fully and that we examine the empirical phenomenon more carefully.

A major obstacle to evaluating the claim for the existence of effector-independent, generalized, motor programs in writing is knowing the level of representation that is common or generalized across the same movement made with different effectors. Saltzman (1979), for example, has proposed a specific sequence of transformations and refinements between the task-level representation of an activity and the specific sequence of muscle activations needed to carry it out. (Arbib's chapter, in this book, discusses another such scheme.) Adopting this framework, the question becomes less one of whether there is effector independence and more one of how up in the representation hierarchy one must go to find the representation common across effectors. Presumably, for instance, all *nominally* identical movements—for example, "Press the button"—are related at the highest, intentional level of representation. But if this is the lowest level of representation common to two instances of that nominal movement task, I would not wish to label this an effector-independent, generalized motor program.

Although the existing data addressing effector independence are suggestive, their usefulness for inferring the existence of or theorizing about the structure of effector-independent, generalized motor programs is limited because these data lack sufficient detail to constrain the space of possible hypotheses. Consider the task of someone attempting to forge your signature. Forgery is possible because we usually only evaluate the gross outlines of a signature, and, relative to the forger's ability to mimic, this evaluation is relatively easy to satisfy. But if, in addition, we examine closely the structural details of a signature, as a handwriting expert might do, the job of the forger is much harder. If, as in done in systems using signature analysis to authenticate identities, we examine information about the kinematics of the signature, then the job of the forger is harder still. The point of this example is simply, what if the motor system is, in some sense, capable of forgery? What I mean by this is, what if, in addition to motor programs that allow us to produce overlearned actions skillfully and fluently with preferred effectors, the motor system is also able to use other effectors on an *ad hoc* basis to simulate some of the salient aspects of such skilled performance. If in evaluating empirical data supporting effector independence we restrict our examination only to those salient characteristics, then we may well be taken in by the "forgery."

This reasoning suggests that along with the aspects of the performance that constitute the primary goal for the performer—for instance, overall trajectory profiles in writing—we should also be looking at other aspects of the performance. One possibility is simply to look for systematic differences in the fine-grained details of nominally identical trajectories produced with different effectors. For example, a close examination of the samples displayed by both Merton (1972) and Raibert (1977) reveals "minor" differences from sample to sample. To some degree, these differences are certainly due simply to variability across individual performances. Unfortunately, without several examples of nominally identical performance from each effector system to compare, we cannot evaluate the contribution of this variability to these differences.

Similarly, we should look at kinematic aspects of performance. As in the case of the forger, these may reveal additional differences across effectors even when similarity of overall trajectory shape is maintained. One possible "forgery" mechanism that might pass tests of shape similarity but that would be revealed by differences in kinematics is the visual-feedback-based, closed-loop strategy typical of unskilled behavior. These unprogrammed performances are, presumably, guided by visual feedback and a nonmotoric conception of what one's writing should look like—in particular, its distinctive features. Using this strategy, unprogrammed performances are controlled by repeatedly deciding on a stroke to make, based on the conceptual representation, making the stroke, and then, after visually comparing the current output with our conception, deciding on the next stroke. The resulting writing performance, although potentially similar in shape to that of the dominant hand, would be typical of unskilled behavior: slow, jerky, uncoordinated, and imprecise.

Overview of a New Experiment

The rest of this chapter describes a new experiment following those of Merton (1972) and Raibert (1977). Although intended as a replication and extension of the previous work, this experiment differs from those on which it is modeled in a number of important ways.

1. This experiment does not include the same effector conditions as either previous experiment. Three effector systems were studied:

   i. the dominant (right) hand writing small as on lined paper (Condition DS);
   ii. the dominant hand writing large as on a blackboard (but note that the graphics tablet on which subjects wrote remained flat on the table), with the subjects instructed to move the stylus primarily with their arm rather than with their wrist and fingers (Condition DL);
   iii. the nondominant (left) hand writing small as on lined paper (Condition NS).

The intent, in these choices, was for writing in the DL condition to be four times larger than that in the DS or NS condition. The obtained ratio was smaller, however.

The comparison of the DS and DL conditions is interesting because these conditions were used in previous studies and this comparison seemed likely to provide as good an example of effector independence as any comparable contrast. The comparison between the DS and NS conditions is also potentially quite interesting. Given the differences in orientation of the dominant and nondominant hands, their laterality differences, and the lack of experience subjects have had writing with their nondominant hand, we might expect that this comparison would not show effector independence. Yet, this comparison was included in Raibert's (1977) demonstration of effector independence, along with others that seem *a priori* even more extreme.

2. This experiment included the manipulation of concurrent visual feedback. As detailed in the Method section, on half of the trials subjects were able to see their complete trajectory on a display screen as they were writing (Condition + V) and on half of the trials they only saw the complete trajectory after the movement was complete (Condition −V). The −V condition was included to disrupt and thus to detect if visual-feedback-based, closed-loop control strategies were being used.

3. In the experiment all subjects wrote two different patterns. In the *NAME*-pattern condition, subjects cursively wrote their common or "short" name: for example, *Craig*, *Michelle*, and so on. This condition was chosen because the writing of one's name in this form is typically (a) short, (b) overlearned, (c) legible (often much more than a full signature), but (d) stylized. Although we do not know with certainty the units of planning and performance in writing, the overlearned and stylized nature of this material may have allowed subjects to use a single, preexisting optimized motor program for the entire string, at least in some conditions, if they ever do such a thing. Finally, although the confounding of material with subjects makes detailed comparison of the writing performances across subjects impossible, it does allow summary comparisons that are directly generalizable across both subjects and stimuli.

In the *EQUATION*-pattern condition, subjects wrote the expression $X + Y = Z$. This expression provides a useful contrast to the material used in the *NAME*-pattern condition in several ways. First, although the expression was undoubtedly familiar to our subjects and probably had been written previously by all of them, it was, presumably, not nearly as overlearned as that in the *NAME*-pattern condition. Probably partially as a result, these performances were not nearly so stylized or distinctive across subjects (although each subjects's hand was clearly distinguishable). In addition, the nature of this material suggested that subjects' performances might be controlled by sequencing subprograms for stroke or letter-sized segments rather than by using a single, highly optimized motor program. Finally, detailed comparisons across subjects are facilitated because the elements of this expression are typically, and always by these subjects, written distinctly in a block writing style. In this style, the strokes making up each element are all, nominally at least, straight lines.

4. This experiment included multiple (20), nominally identical performances for each of the three effector systems studied with each of six subjects. This richer data set allows evaluation of whether observed differences between instances represent systematic or random variation.

5. As detailed in the Method section, this experiment used different technology to collect and store the data. This change allows more and better data to be collected but also may have affected subjects' writing strategies.

METHOD

Subjects

The data reported here are from the first of two hour-long sessions for 6 right-handed Columbia University undergraduates. They received $5.00 per hour for their participation.

Design

In each session, a subject produced 130 repetitions in one of the two pattern conditions: *NAME*-pattern or *EQUATION*-pattern. The *NAME*-pattern condition was always run first.

The 130 repetitions (hereafter *trials*) of each pattern, were divided into 13 blocks of ten trials each. Subjects were instructed that the ten trials in each block were to be as close to exact repetitions as possible. The blocks differed in the effector and manner with which subjects were instructed to write (DS, DL, and NS effector conditions) and the presence or absence of concurrent visual feedback (+V, −V feedback conditions). The combination of the three effector systems and two types of concurrent visual feedback produced six conditions, each of which was studied in two of the 12 blocks of ten test trials. The first block of trials was considered practice and was always done in the DS+V condition. The order of conditions within a subject was balanced so that linear practice effects could be averaged out. The within-subject orders were further balanced across subjects using several Latin squares.

Apparatus

The data were collected using an IBM-AT compatible computer with a Summagraphics Model 1812 digitizing tablet (resolution of 1000 points per in. on each dimension of its X, Y coordinate system). The inductive sensing system of this digitizer allows position information to be collected whenever the stylus is within approximately 1.25 cm of the digitizer surface (there is some loss of accuracy when the stylus is off of the tablet surface since stylus orientation also affects the position sensed). X-Y coordinate pairs were sampled and stored 110 times per sec by the computer along with the sample time, measured to millisecond accuracy using a Metrabyte clock card. The computer presented visual information to the subject on a 25-cm by 18-cm NEC color graphics display driven by a QuadRam EGA+color display board (running in mode 16 with 640 × 350 resolution and a 60 Hz noninterlaced refresh rate).

Subjects wrote using a stylus with a nylon tip on the surface of the digitizer. Subjects were able to see the current position of the stylus and their hands. However, because the stylus left no marks on the digitizer surface, the trajectory up to the current point could only be seen if the computer presented it on the display screen. This display sat directly behind the digitizer, with its screen almost perpendicular to the digitizer surface. Although this is not an ideal arrangement for concurrent visual feedback manipulation because subjects had to look up from their hand to see the screen, it was possible for subjects to view the screen without moving their heads.

For each effector system there was a rectangle visible on the surface of the digitizer: For the DS and NS conditions the rectangle was 1.91 cm high by 7.62 cm wide and for the DL condition it was scaled proportionately, 7.62 cm high by 30.48 cm wide. Subjects were instructed that their writing should stay within the rectangle, approximately filling it in one dimension. Displays of writing performance were scaled for each effector condition, to maintain the aspect ratio of the actual performance. The box visible to the subject on the digitizer was mapped on a similar outline displayed on the screen, which was approximately 5.72 cm high and 22.86 cm wide.

Procedure

The experimenter remained with the subject throughout each session. At the beginning of each block, a display informed the subject about the visual feedback and effector conditions for that block. The experimenter made sure that the subject understood these instructions and then pressed a key on the keyboard connected to the computer to begin the sequence of trials.

Data recording began when the subject touched the stylus down on the surface of the digitizer. Once data collection began, the subject had 15 sec to finish writing. Data collection ended after the subject lifted the stylus off the surface of the digitizer for more than 750 ms. After each trial, the computer displayed what the subject had written (this amounted to simply leaving up the display drawn during the trial in blocks with concurrent visual feedback). The data points recorded with the stylus off the surface of the digitizer were excluded from these feedback displays. When this display indicated a systematic problem or confusion on the part of the subject, the experimenter pointed this out; otherwise the experimenter simply waited to initiate the next trial when the subject indicated a readiness to proceed. Because there was no norm against which to compare each performance, no scores or other systematic feedback about the performance were given to the subjects.

Data Reduction

To aid in further analyses, a semiautomated procedure was developed to identify analogous stroke endpoints across each of a subject's repetitions of a response. This was done after each subject had finished the experiment. Underlying this procedure is the assumption, which I simply accept from the work of others (Denier van der Gon & Thuring, 1965; Hollerbach, 1981; Morasso, Mussa-Ivaldi, & Ruggiero, 1982; Viviani & Cenzato, 1985), that the stroke constitutes a basic unit of analysis and performance in handwriting.

To begin the process of segmentation, possible stroke endpoints were identified automatically using an algorithm that identified local minima of sufficient depth in the tangential velocities. The experimenter then worked interactively with the computer to select which of these potential endpoints matched the stroke endpoints in a previously segmented prototype movement. Prototype trials were chosen based on their representativeness and fluency from the set of trials made using the DS effector with concurrent visual feedback. All 130 trials for each subject were then marked to match this prototype. The coordinates of the resulting marked points as well as characterizations of the strokes between the marks were the basis of the remaining analyses.

The decision embedded in this procedure to force the marking of each performance to match that of the prototype is based on the premise that all 130 trials represent a single underlying target pattern realized through a noisy transmission channel. With this procedure, I hoped to maximize the possibility that effector independence would be revealed if it exists.

The experimenter-directed part of this marking process. although usually straightforward, did occasionally require substantial judgment. Among the more describable of the problems encountered were: (a) cases where two usually distinct strokes were coalesced into a single, looping stroke, (b) cases where some feature was omitted, added, or transformed, usually throughout a condition, and (c) cases where the subject simply appeared to be confused about the task. In addition, the automatic stroke-identification algorithm often ran into problems when subjects wrote slowly and deliberately in the NS condition. I never excluded trials from analysis because of these marking problems because that might have introduced a poorly understood sampling bias. Occasionally, however, not all marks could be placed for every trial, and later analyses had to be tailored to deal with the resulting uncertainty in the data.

RESULTS

Comparison of Single Movements

At the level of analysis previously used, the data from this experiment replicate and extend the studies of Merton (1972) and Raibert (1977) in that the overall shape of the written strings displayed marked similarities across effectors for both pattern types. Figures 9.1 and 9.2 give some idea of both this similarity in shape and the variability across instances for replications by a single subject. Figure 9.1 shows 10 repetitions by one subject in the *NAME*-pattern DS + V and NS + V conditions. Figure 9.2 allows the same type of comparison for a different subject in the *EQUATION*-pattern DS − V and NS − V conditions. Although these figures provide a useful "feel" for the data, to get a clearer impression of what subjects were trying to accomplish in each condition, it is more useful to compare average performances rather than the individual instances shown in these figures.

Comparison of Averaged Movements

Averages were computed for the "markable" trials that each subject produced for each patten (there were between 18 and the maximum of 20). These averages were obtained through an iterative process. This involved first rotating, translating, and scaling all of the instances produced by a subject for a pattern. These transformations were done so that the marked points in each instance made the best possible match to their analogues in the current best estimate of the "average" performance. These transformed instances were then summed to create a new estimate of the average across conditions and the entire process was repeated. Once the overall averages produced by this process stabilized (usually after only two or three iterations), the transformed instances were averaged separately for each of the six combinations of effector and concurrent visual feedback. These averages by condition include not only the marked points but ten interpolated points spaced evenly in time between each pair of marked points. These interpolated points allow the average trajectories to be visualized and compared in more detail.

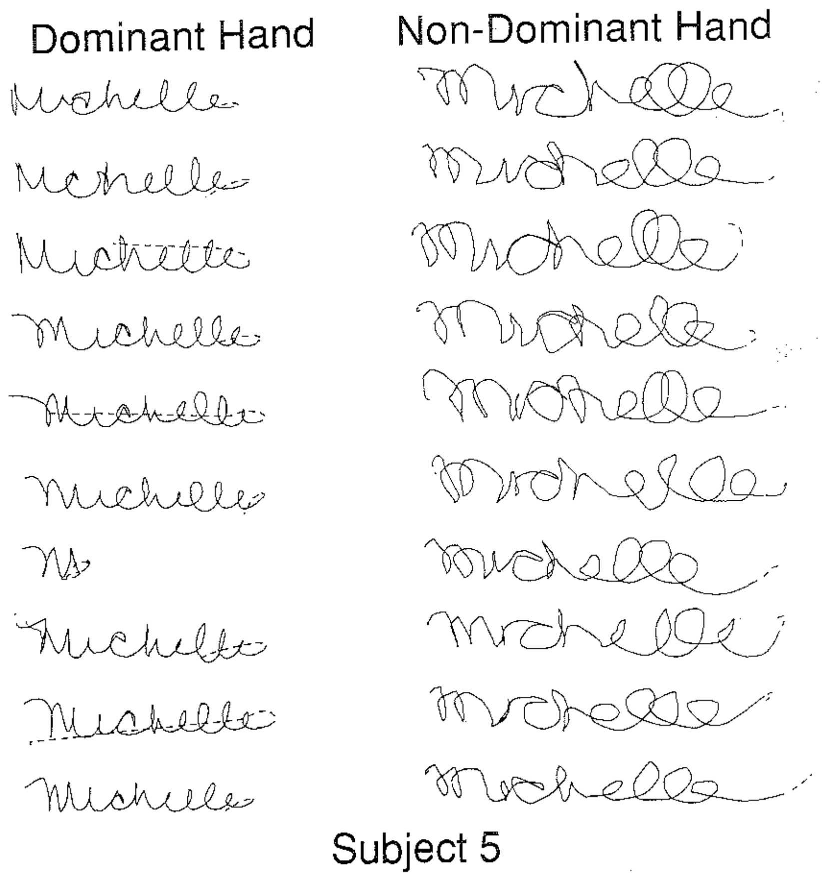

FIG. 9.1. Comparison of ten trials (one block) in the *NAME*-pattern DS + V and NS + V conditions for one subject. Solid lines were made with the stylus on the digitizer surface; dashed lines were recorded with the stylus off the digitizer surface.

Examples of the results from this averaging process can be seen in Figs. 9.3 and 9.4. These figures display comparisons of the average performance across trials in all six conditions. The crosses at the bottom left corner of each frame represent a pooled estimate of ± 2 standard errors of the mean (each line has a total length of four standard errors of the mean) for each point in these average trajectories.[1]

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[1] Except for a few isolated cases, typically occurring near the ends of the trajectories or where the stylus was off the surface of the digitizer, the standard deviations at the individual points were reasonably homogeneous across a trajectory.

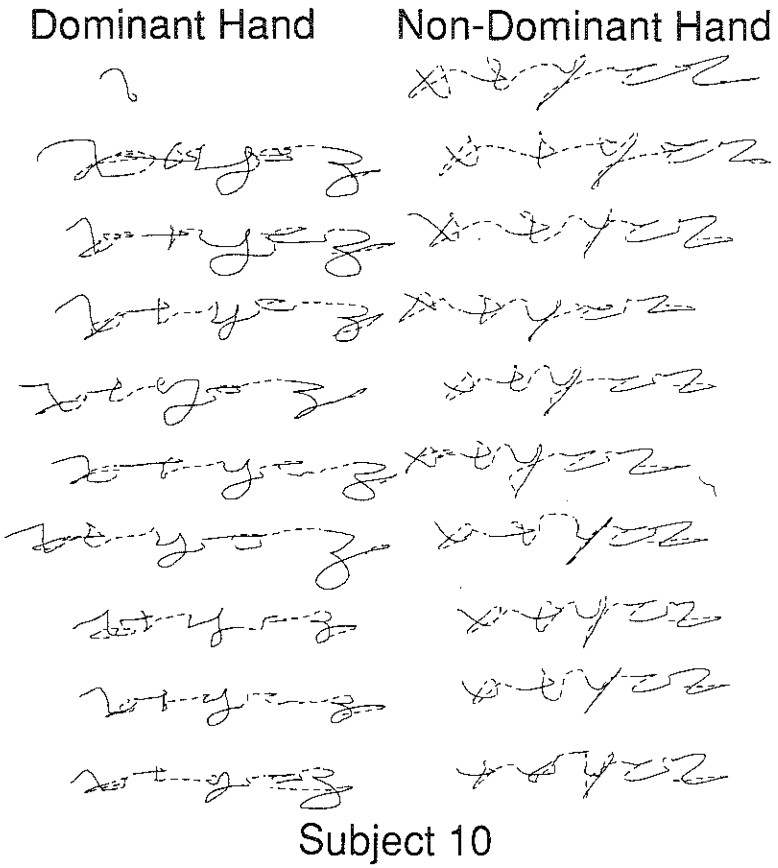


FIG. 9.2. Comparison of ten trials (one block) in the *EQUATION*-pattern DS−V and NS−V conditions for one subject. Solid lines were made with the stylus on the digitizer surface; dashed lines were recorded with the stylus off the digitizer surface.

Like the individual movements displayed in Figs. 9.1 and 9.2, the averages in Figs. 9.3 and 9.4 show clear similarities across conditions. What these averages reveal just as clearly is that there are differences between the average performance in different conditions, and these differences are systematic, not merely trial-to-trial variation. These differences tend to be most striking for comparisons involving conditions with the nondominant hand (NS) and one of the other two effector conditions (DS and DL). Although they are usually less dramatic, there also are systematic differences between the two conditions performed with the dominant hand (DS versus DL) and the conditions performed with and without concurrent visual feedback (+V and −V).

Notice the formation of the letter *K* in Fig. 9.3, for example. Typical of the first letter in many signatures, the subject forms this letter from four strokes in a fairly ornate style. The first stroke is a vertical stroke starting at the top of the letter. The second stroke, which is off the surface of the digitizer, returns from the bottom of the letter to its upper right-hand corner. The third stroke is the diagonal from the upper right back to the midpoint of the vertical line. This stroke starts out as a wide curve that

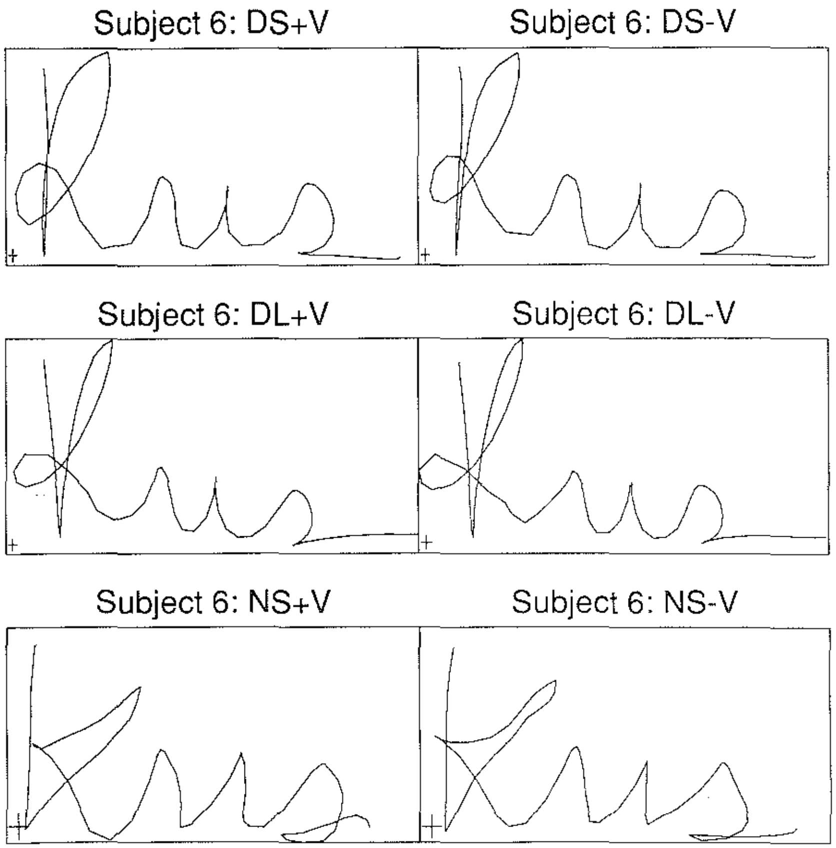
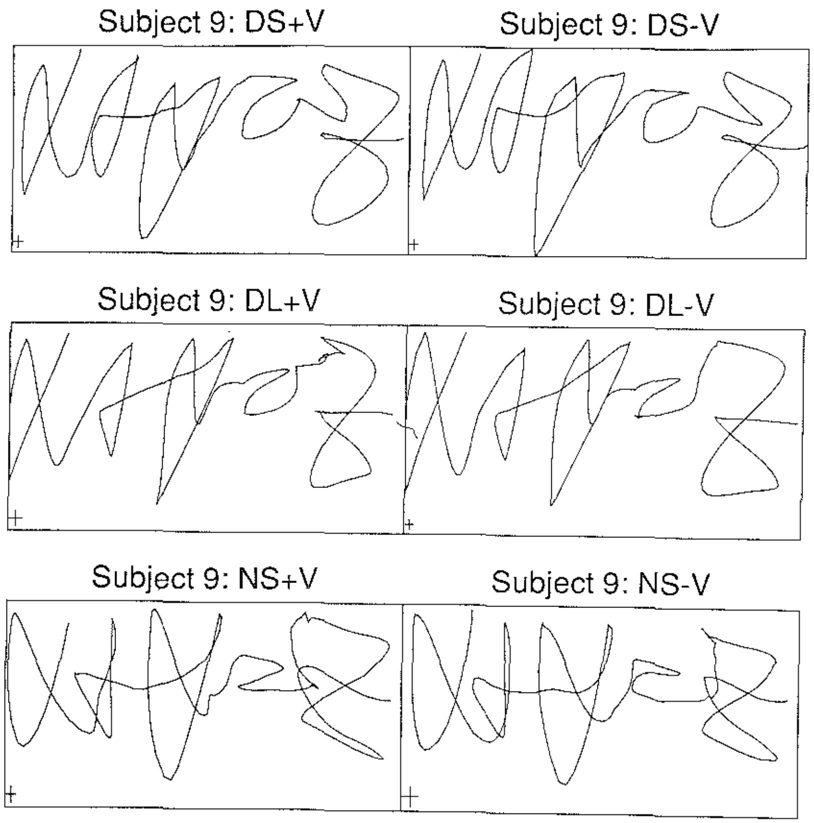


FIG. 9.3. The average performance of one subject writing the *NAME*-pattern is each of the six conditions. Note that the averaging process did not distinguish strokes made with the stylus on the surface of the digitizer and those made with the stylus off the digitizer surface.



Subject 9: DS+V

Subject 9: DS-V

Subject 9: DL+V

Subject 9: DL-V

Subject 9: NS+V

Subject 9: NS-V

FIG. 9.4. The average performance of one subject writing the *EQUATION*-pattern in each of the six conditions. Note that the averaging process did not distinguish strokes made with the stylus on the surface of the digitizer and those made with the stylus off the digitizer surface.

tightens to form the lower half of a loop at the vertical line, the characteristic embellishment of this subject. The fourth stroke begins at the back of this loop, forms its top, and then continues down and right to lead into the next letter.

This description is accurate for all four conditions in which the dominant hand is the effector (DS and DL). When this subject writes with the nondominant hand (the NS conditions), however, the characteristic loop is largely eliminated. And, although the subject still maintains the four stroke composition of this letter, the relationship between these stokes also changes somewhat. In both NS conditions, stroke two, instead of starting by retracing the path of the first (vertical) stroke, immediately heads off to the right side of the character. In the process, this stroke fails to reach the top of the character, causing stroke three to be closer to horizontal than normal.[2]

The same modifications already noted for movements made with the nondominant hand also occur, although less dramatically, for movements made with the dominant arm (DL conditions) and movements made without the aid of concurrent visual feedback ($-$V conditions). Thus the area of the loop bounded by strokes three and four is larger for the DS + V condition than in these other three conditions [for the comparison with DS $-$ V, $F(1,5) = 6.95$, $p = .06$; for the comparison with DL + V, $F(1,5) = 20.03$, $p < .01$; for the comparison with DL $-$ V, $F(1,5) = 18.27$, $p < .01$].

Similarly, the loop bounded by strokes two and three is larger in the DS + V condition than in these other three conditions [for the comparison with DS $-$ V, $F(1,5) = 16.35$, $p < .01$; for the comparison with DL + V, $F(1,5) = 25.83$, $p < .005$; for the comparison with DL $-$ V, $F(1,5) = 63.18$, $p < .001$]. Along the same lines, note that the point where strokes three and four cross over is out to the right farther from the first vertical stroke in the DS conditions than in the DL conditions, whereas stroke two is back closer to vertical stroke one in the DS conditions than the DL conditions.

Interestingly, the presence or absence of visual feedback appears to have had no effect for this last pair of comparisons. Similarly, although the absence of concurrent visual feedback reduced the area of the loops in the DS conditions, there was no equivalent effect for the comparisons between the DL conditions [for the loop formed by strokes three and four, $F(1,5) = 0.82$; for the loop formed by strokes two and three, $F(1,5) = 2.13$, $p > .25$]. Visual inspection of the NS conditions suggests that there was also little systematic effect of concurrent visual feedback on this effector.

Although the exact nature of these differences across effectors and the presence/absence of concurrent visual feedback depend strongly on the subject and the pattern, it is a reasonable summary that similar patterns of systematic differences occur for all six subjects and both patterns. These analyses have concentrated on changes in large features. Figure 9.5 provides examples of comparisons that reveal differences at a subtler level.

Figure 9.5 shows, superimposed, the average trajectories for one subject (named Thomas) writing the *NAME* pattern in the NS + V condition and

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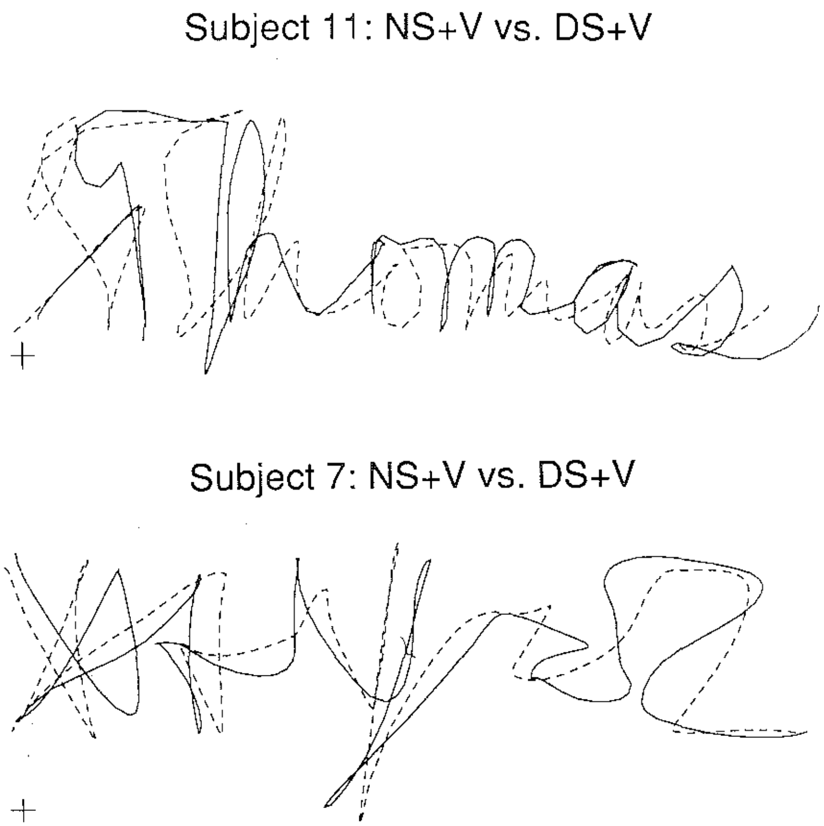
[2] Note that the tendencies discussed here are not artifacts of averaging, but, instead, are typical of most of the individual trials of each type.



Subject 11: NS+V vs. DS+V

Subject 7: NS+V vs. DS+V

FIG. 9.5. Superimposed average performances of one subject (Thomas) writing the *NAME*-pattern in the NS+V (solid line) and DS+V (dashed line) conditions and one subject writing the *EQUATION*-pattern in the NS−V (solid line) and DS−V (dashed line) conditions. Note that the averaging process did not distinguish strokes made with the stylus on the surface of the digitizer and those made with the stylus off the digitizer surface.

the DS+V condition. Figure 9.5 also shows a similar comparison for a different subject in the *EQUATION*-pattern condition. The cross at the lower left corners represent a pooled estimate of ± 2 standard errors of the mean difference between corresponding points (each line has a total length of four standard errors of the mean) for each point in these average trajectories. The two average trajectories have been scaled and oriented to maximize their overlap. Despite this, it is clear that there are changes in the relative size of parts of these averages as well as changes in the way the space within them is used.

Comparison of Kinematic and Other Summary Data

I now turn from descriptions that depend on the shape of the trajectory to other aspects of the writing performance: stroke composition, duration, and peak velocity. These aspects of the writing behavior tell a consistent story across subjects and the two pattern conditions. To summarize, the dominant hand writing small (DS condition) was fluent and quick. There is some suggestion that writing large letters with the dominant hand (DL condition) was somewhat less fluent, although it was as stable across repetitions. Finally, writing with the nondominant hand (NS condition) was clearly less fluent, slower, more jerky, and more variable across repetitions.

The data supporting this summary are in Table 9.1. Within this table, each line breaks out one aspect of performance by the pattern and effector conditions. Although there were systematic effects of the visual feedback condition within the data of individual subjects, the pattern of these effects was not consistent across subjects. The data in Table 9.1 are, therefore, averaged across visual feedback condition. Thus, each cell in Table 9.1 is the average of roughly 40 replications for each of 6 subjects. For each pattern condition there is also a 10-degree of freedom, pooled estimate of the repeated-measures, standard error for each of the three means.

Line 1 of Table 9.1 shows the total trajectory length measured from the beginning of the first marked stroke to the end of the last marked stroke, including strokes made both on and off the digitizer surface. There is no reliable difference in this length between the DS and NS conditions. The length in the DL conditions is roughly 2.5 times that in the DS conditions. This ratio is less than the target of 4.0 that I had hoped the stimulus conditions would induce.

Line 2 of Table 9.1 shows the time, in seconds, from the beginning of the first marked stroke to the end of the last marked stroke. In both pattern conditions, this time increases systematically from the DS to the DL effector conditions and additionally from the DL to the NS effector conditions. Although an increase in time by a factor of 1.25 between the DS and DL conditions may seem plausible given an increase of 2.5 in the trajectory length, this finding was somewhat unexpected in light of previous research involving size changes in handwriting. For example, Hollerbach (1981, p. 153) states: "Handwriting frequency is independent of writing size. This independence is an accepted observation in the handwriting literature (Denier van der Gon & Thuring, 1965; Yasuhara, 1975) and is an observation substantiated in my own measurements." I can only spec-

TABLE 9.1.
Summaries of writing behavior by pattern type and effector condition averaged across visual-feedback conditions and subjects (occasionally also segments).

Measure	*Units*	*NAME-Pattern*			*Pooled StdErr*	*EQUATION-Pattern*			*Pooled StdErr*
		DS	*DL*	*NS*		*DS*	*DL*	*NS*	
1. Trajectory Length	cm	50	112	44	10	31	84	34	2.0
2. Duration	s	2.21	2.78	4.01	0.11	2.74	3.41	4.35	0.14
3. Average Tangential Velocity	cm/s	24	43	12	4.6	11.7	25.3	8.1	0.66
4. Peak Tangential Velocity	cm/s	52	91	35	5.0	49	94	35	4.1
5. Number of Extra Segments		0.66	0.89	1.98	0.15	0.45	0.71	1.36	0.08
6. Std-Dev X Coordinates	*	11.0	11.9	20.6	1.4	14.1	15.1	21.6	1.1
7. Std-Dev Y Coordinates	*	6.7	6.9	11.5	0.5	8.1	8.8	12.3	0.5

*The standard deviations were computed after size normalization and so have arbitrary units of length.

ulate on the source of this discrepancy without further investigation; however, a critical difference appears to be that subjects in the current experiment were explicitly instructed to form their larger trajectories using their arms instead of their hands, whereas subjects in previous experiments may have produced instances of writing at different sizes using the same effectors.

If, as previous theories suggest (Denier van der Gon & Thuring, 1965; Hollerbach, 1981), invariant movement time is a critical element of the motor representation underlying handwriting, then this difference between the DS and DL effector conditions indicates different motor programs may have controlled the performances in these conditions. This indication receives some further support from the fact that the size of this increase is remarkably stable across the pattern conditions (1.26 in the *NAME*-pattern condition and 1.24 in the *EQUATION*-pattern condition; a 95% confidence interval for the difference of these values is ± 0.06). The much larger difference in writing time between the DS and NS effector conditions (1.7 to 1) supports this indication even more strongly because this difference cannot be attributed to any differences in the size of the trajectories.

Line 3 of Table 9.1 shows the average tangential velocity in each segment pooled across the segments. In these data there are reliable differences between all the effector conditions for both pattern conditions.

Line 4 of Table 9.1 shows the peak tangential velocity in each segment pooled across the segments. Once again, there are reliable differences among all the effector conditions for both pattern conditions: Peak velocity is higher in the DS than in the NS condition and still higher in the DL condition. These data also allow an intriguing comparison between the DS and DL effectors across the two pattern conditions. For the *NAME*-pattern condition, there is an increase in movement duration going from the DS to the DL effector of 1.26 and an increase in peak velocity of 1.75. The product of these two increases, 2.20, almost perfectly matches the actual increase in the trajectory length, 2.24. This outcome is consistent with models of movement control in which changes of distance and/or time are achieved by rescaling a velocity profile whose shape is invariant (e.g., Meyer, Smith, & Wright, 1982). For the *EQUATION*-pattern condition, there is an increase in movement duration going from the DS to the DL effector of 1.24 and an increase in peak velocity of 1.92. This increase in peak velocity is not, however, sufficient to allow the product of these two increases, 2.38, to match the actual increase in the trajectory length, 2.71. This discrepancy means that the shape of the velocity profile must be different for these two effectors in the *EQUATION*-pattern condition. Confirmation and an explanation of this discrepancy must await further detailed analyses.

Line 5 of Table 9.1 shows the number of "extra" potential segment boundaries within each marked segment. The Methods section describes how each instance of a written pattern was segmented into a fixed set of strokes by marking stroke endpoints. The stroke endpoints for this analysis were determined by an algorithm that identified local minima in the tangential-velocity profile. Although all marks were constrained to fall at stroke endpoints, not all of the potential stroke endpoints found by this algorithm were used as the basis of marks. The stroke-composition measure, then, is simply the count of potential stroke endpoints occurring between each pair of marks. Whereas the absolute number of the endpoints determined by the algorithm depends on details of the algorithm itself, the relative number of these endpoints found across conditions should indicate the fluency of the writing activity.

As Line 5 shows, even the DS condition reliably contained such extra potential stroke endpoints. In this condition, most of the extra endpoints appear, however, to be due to positioning movements made with the stylus off the surface of the digitizer. The number of extra endpoints increased somewhat in the DL condition: The 34% increase for the *NAME*-pattern condition is not reliable across subjects, whereas the 73% increase for the *EQUATION*-pattern condition is reliable. The increase in the number of extra endpoints between the DS and NS effector conditions is more substantial and consistent across the pattern conditions: There is a 258% increase for the *NAME*-pattern condition and 231% increase for the *EQUATION*-pattern condition, both reliable across subjects. These large increases suggest the writing was decomposed into smaller strokes in the NS condition. Presumably, concatenating many smaller strokes either requires less coordination or reduces the possibility of large, unacceptable spatial errors.

Lines 6 and 7 of Table 9.1 show the average standard deviations of the x,y coordinates for the marked points, computed after the transformations to align the movement instances. Because these standard deviations were computed after rescaling, any tendency for endpoint variability to vary proportionally with movement size is eliminated. In fact, these standard deviation estimates are virtually identical across the DS and DL effector conditions; the small increase in Table 9.1 is not reliable across subjects. These variability measures do, however, increase substantially and reliably between the DS and NS effector conditions, consistent with the suggestion that movements in the NS condition are less precise and thus less fluent.

DISCUSSION

This research begins an attempt to use the phenomenon of effector independence in handwriting as a tool to gain a better understanding of the

motor representations used to control complex movement sequences and, in particular, to better understand how motor programs can be generalized. To make this phenomenon more useful as a tool, it is necessary to begin by identifying some of its limits. Just as the linguist's search for language universals starts by identifying features that do and do not change between languages, so, I hope, a better understanding of how motor programs are generalized can emerge by studying the features of writing movements that are and are not invariant across effectors.

General Summary

Extending the previous work of Merton (1972) and Raibert (1977), the data reported here demonstrate that, at the level of overall shape, the trajectories of highly overlearned and less-well-practiced writing movements are similar when performed, with or without concurrent visual feedback, by any of the three effector systems studied. Perhaps more importantly, these data also demonstrate that changing effector system or removing concurrent visual feedback both lead to changes in the details of the written trajectories. These changes in detail are systematic across repetitions, and, thus, they are not simply due to the variability of particular instances or the lack of skill in the use of particular effector systems. The data reported here also reveal reliable differences across effectors in measures of kinematics, fluency, and repeatability of the writing movements. These differences need not be interpreted as violations of the principle of effector independence; rather, their importance lies in the limits these differences circumscribe for the generality of this observation.

Along more theoretical lines, we can ask, to continue the analogy drawn in the Introduction, whether the differences observed for writing with different effectors constitute "forgery." Alternatively, these differences could be interpreted as predictable changes occurring when a single, effector-independent, generalized motor program is carried out by effector systems with somewhat different properties. If we consider these differences to be consistent with the hypothesis of a single, effector-independent, generalized motor program, then we must also address the question of the level of specification common to the performance across effectors. Of course, the second version of this question might be considered logically to subsume the first.

Dominant Versus Non-Dominant Hand

Evaluating the comparison between the dominant and the nondominant hand for evidence of a forgery, we might conclude that, as such, it is fairly inept. Although the overall shape of the written trajectory is preserved, many salient details of that trajectory are noticeably altered. In addition, writing with the nondominant hand is less fluent. Simply because subjects are less practiced writing with their nondominant hand, we might expect this hand to be slower and to have lower spatial accuracy across repetitions. More telling is the observation that writing with the nondominant hand uses a different decomposition of letters into strokes, involving many more, smaller strokes. If, as several authors suggest (e.g., Edelman & Flash, 1987; Hollerbach, 1981; Viviani & Cenzato, 1985), strokes constitute the primary level of organization for the planning of writing movements, the difference in stroke composition for two versions of the same movement suggests that these movements were produced according to different plans or motor programs. And, if we consider these movements to have been produced under the control of a single program, that program must be quite abstract, incorporating little more than overall shape information and almost nothing strictly motoric.

To my mind, a more plausible explanation for these observed differences is that writing with the nondominant hand is controlled in a different way than writing with the dominant hand. One obvious candidate for an alternative mechanism is the process of successive approximation based on feedback typical of unskilled activities. This is not, of course, to imply that writing with both hands could not, perhaps after sufficient practice, be controlled by the same motor program but that for the tasks, subjects, and level of practice involved here, this was not the case. One possible problem with this interpretation is the expectation, outlined in the Introduction, that writing produced using successive approximation based on feedback might use a feedback loop involving, specifically, visual feedback. In this case, I would have expected performance to depend critically on the availability of concurrent visual feedback. The results are inconsistent with that suggestion. If the suggestion had been correct, I would have expected removal of concurrent visual feedback to have had dramatic negative effects on performance with the nondominant hand. Although removing concurrent visual feedback had a measurable impact, this manipulation did not cause major disruptions. However, as noted in the Method, the procedure used to manipulate the presence of concurrent, visual feedback in this experiment was, for practical reasons, perhaps less than ideal. It is possible that a more natural manipulation of concurrent visual feedback would lead to larger effects. This is a possibility that has to be explored in future research.

Small Versus Large Writing with the Dominant Hand

The differences observed in the comparison between the DS and DL conditions, the dominant hand writing small as on a piece of paper versus the dominant hand and arm writing large as on a blackboard, are more subtle because the similarities are much stronger. Evaluating this comparison for evidence of "forgery" would be much more difficult because, although there are systematic differences in performance at various levels of analysis, no difference itself is compelling. Once again, the overall shape of the writing is similar, and, in fact, it is necessary to make a careful examination of the fine details of each stroke before any differences become apparent.

Without having a formal analysis to support this supposition, it is plausible to me that movements made with different effectors controlled by a single effector-independent, generalized motor program would result in systematic, if subtle, differences in trajectory. Consider, for example, the model for handwriting proposed by Hollerbach (1981). In this model, cursive writing movements are represented as changes in the parameters of two coupled oscillators: one operating in the direction of a superimposed, constant rightward movement, and the other operating in a direction roughly orthogonal to the first. The assumption of effector independence comes in the supposition that the degrees of freedom of the effector system used for writing can be organized into functional synergies that implement the required, orthogonally coupled oscillators. If, however, the *virtual effector* created by these synergies differs, even slightly, when implemented using the arm as opposed to the hand, then we would expect minor, systematic differences in the observed trajectories.

The observed difference in movement times between the DS and DL conditions is suggestive of a change in control strategy or motor program, but far from conclusive. These results suggest this because it is well accepted that the writing control system acts to keep movement times constant across variations in movement size and stylus friction (Denier van der Gon & Thuring, 1965; Hollerbach, 1981; Yasuhara, 1975). These results are not conclusive because it is unclear if the earlier results on which this conclusion is based involved comparisons across effectors. It is plausible that an effector-independent, generalized motor program for writing would include relative, not absolute, timing information that could then be transformed differently by the functional synergies used to implement this program for different effectors. This possibility suggests the desirability of a controlled comparison of timing invariance in writing within and across effectors.

Finally, two differences between the DS and DL effectors that occur only in the *EQUATION*-pattern condition might be taken to suggest that an effector-independent, generalized motor program was operating in the *NAME*-pattern but not the *EQUATION*-pattern conditions. First, as in the comparison of the DS and NS effectors, there is an increase in the number of potential stroke endpoints with the DL effector. As before, this can be taken to suggest a different decomposition of letters into strokes. However, this conclusion is less persuasive than in the previous comparison both because the increase is smaller and because I cannot be certain that this increase is not an artifact due to an interaction between the larger stroke sizes with the DL effector and the algorithm used to identify potential stroke endpoints.

The second of these differences has to do with the relative size of the increases in trajectory length, duration, and peak tangential velocity. As outlined in the Results, the size of the increase in trajectory length going from the DS to the DL effectors can be accounted for in the *NAME*-pattern condition by the simultaneous increases in duration and peak tangential velocity according to the principles of velocity-profile rescaling. A similar accounting does not work, however, in the *EQUATION*-pattern condition. Because invariance of velocity profile across effectors is a stronger constraint than invariance of trajectory shape, this result might also be interpreted as evidence for the operation of an effector-independent, generalized motor program in the *NAME*-pattern but not in the *EQUATION*-pattern condition. However, before giving credence to this possibility, the underlying assertion about the velocity profiles can and should be tested directly.

CONCLUSIONS

This chapter reports the application of several detailed analyses of writing data designed to provide a clearer idea of the generality and limits of effector independence in writing. Confirming the previous observations that overall shape is strikingly similar across effectors, these analyses also confirm that changing effectors results in systematic changes in details of shape, kinematics, stroke decomposition, and fluency. Clearly, more work needs to be done refining and extending these analyses before we have a complete picture of what stays the same and what differs when the effectors used for writing are changed.

I have used the preliminary results reported here to reopen the discussion of the implications of effector independence in writing for the hypothesis that motor programs can be generalized to operate across effectors. I believe this discussion should be reopened because the previously existing evidence of shape similarity across effectors only weakly constrains the set of possible explanations. Although it is early to make strong assertions, I believe the results reported are consistent with the conclusion that writing by the dominant and the nondominant hands is carried out using different strategies that share only the very highest and most abstract spatial representations of what the shape of the writing should be. By contrast, writing with the dominant hand and the dominant arm appear to be controlled by mechanisms that share a common representation much lower in the hierarchy of increasing motor specificity particulary for highly overlearned productions such as one's name.

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ATTENTION and PERFORMANCE XIII

Motor Representation and Control

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