ON THE COORDINATION OF TWO-HANDED MOVEMENTS

J. A. Scott Kelso,† Dan L. Southard,** and David Goodman

Abstract. In a set of three experiments, we show that after an auditory "go" signal, subjects simultaneously initiate and terminate two-handed movements to targets of widely disparate difficulty. This is the case when the movements required are (a) lateral and away from the midline of the body (Experiment 1), (b) towards the midline of the body (Experiment 2), and (c) in the forward direction away from the body midline (Experiment 3). Kinematic data obtained from high-speed cinematography (200 frames/sec) point to a tight coordinative coupling between the hands. Although the hands move at entirely different speeds to different points in space, times to peak velocity and acceleration are almost perfectly synchronous. We promote the viewpoint that the brain produces simultaneity of action as the optimal solution for the two-handed task by organizing functional groupings of muscles—coordinative structures—that are constrained to act as a single unit.

INTRODUCTION

Recent theoretical development in motor behavior has focused to a considerable degree on the issue of whether movements are under closed-loop (feedback) or open-loop (programmed) control (Adams, 1971, 1977; Schmidt, 1975). Much of the data has been generated from linear positioning tasks involving the use of a single limb. In contrast, little is known about the principles governing interlimb coordination, even though much of human movement involves the coordinated participation of both hands and hence the concerted operation of the cerebral hemispheres (Luria, 1973). Part of the reason for this state of affairs may be that coordination does not lend itself easily to quantification. Rather, we seem content to rely on anecdotal evidence for insight into such problems.1

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In this paper we present three experiments on a behavioral task that involves coordination of the upper limbs. Combined with high-speed cinematographic movement analysis, the findings elucidate the mode of control utilized by subjects when faced with a task that places different movement demands on each hand. Our question was a simple one. Suppose an individual is asked to produce movements of the upper limbs to targets each of which varies in amplitude and precision requirements; How will he or she respond? A relationship between movement duration, movement amplitude, and target demands, formulated some time ago by Fitts (1954), allows us to examine this question experimentally. The equation relating the foregoing parameters is known as Fitt's Law, in which movement time = a + b log2 (2A/W), where a and b are constants, A is the amplitude of the movement, and W is the width of the target. The key aspect of this formulation is that movement time depends on the ratio of movement amplitude to movement precision. Thus, the movement time for a 4-cm movement to a .5-cm target width (8:1 ratio) is practically identical to an 8-cm movement to a 1-cm target.

Consider a one-handed movement condition in which the target size is large and the amplitude short (termed easy), relative to a condition in which the target size is small and the movement amplitude is long (termed difficult). Movement time in the former case will obviously be shorter in duration. But what happens when these conditions are combined for both hands? Does the hand producing a short movement to an easy target arrive much earlier than the more difficult condition or are the movements initiated and terminated simultaneously?

A pilot experiment was conducted to examine this question. Ten subjects performed single- and two-handed movements (involving extension of the wrist-forearm linkage) of equal and varying difficulty as quickly and as accurately as possible, following an auditory stimulus. A major finding was that movement times for the easy task under combined conditions (that is, easy for one limb and difficult for the other) were nearly doubled compared with single limb counterparts and conditions where both hands performed the easy task. The hand moving to the easy target under combined conditions therefore appeared to wait for the hand traveling to the difficult target so that they could strike together. This finding indicates that in spite of differences in target demands and movement length between each hand, response duration appears to be held constant. Duration, then, could be interpreted as a major parameter in the program for two-handed movements. One of the drawbacks of the pilot experiment was that subjects were instructed, at the onset of an auditory signal, to leave the home keys simultaneously. Indeed, trials in which reaction time differences between the hands were greater than 15 msec were excluded. Although this criterion was exceeded on a very small proportion of trials, we felt that the emphasis on simultaneous reaction time may have biased subjects to also terminate the movements simultaneously. The procedure in Experiment 1, therefore, was simply to instruct the subjects to strike the designated targets as quickly and as accurately as possible, without any reference to reaction time simultaneity. We felt that removal of this potential bias would provide a clearer picture of how the limbs perform under combined conditions.
EXPERIMENT 1

Method

Subjects. The subjects were 12 right-handed volunteers ranging in age between 18 and 25 years. One subject's results were excluded from the data analysis because limited peripheral vision prevented his performing the task in certain movement conditions without an exceptional number of errors. Although the subjects were not paid individually for their participation, a five dollar bonus was awarded to the most accurate subject with the best overall response times (i.e., combined reaction times and movement times).

Apparatus. The apparatus consisted of a Plexiglas base (76 cm in length, 16 cm wide, and .8 cm thick) mounted on a standard table (76 cm high) such that the long edge of the base was parallel to the front edge of the table. Two normally closed momentary-contact switches (Cherry keyboard switch, Model #M62-0900), centered 4.5 cm apart, served as the home keys. The base was constructed so that two hinged masonite targets could be positioned along the longitudinal center line of the base, anywhere from 2 cm to 32 cm in distance from the home keys. Two target widths were used: The "easy" target was 7.2 cm wide and the "difficult" target was 3.6 cm wide. These were located at either a short distance (6 cm) or a long distance (24 cm) from the home keys. A single target was used in single-hand conditions and two targets in the double-hand condition, allowing all combinations of target width and target distance to be utilized. A red light-emitting diode served as the warning light and the sound from a Minisonalert provided the stimulus to move. These were mounted on a 50 cm x 15 cm board centered 10 cm behind the apparatus, directly in front of the subject. The onsets of warning light and stimulus tone were controlled by a PDP8/A computer that also collected reaction times, movement times, and total response times.

Task. The subject's task was to move his or her index fingers from the home keys to the targets as fast and as accurately as possible after receiving the auditory stimulus from the Minisonalert. For single-hand conditions, the subject depressed the left home key with the left index finger or the right home key with the right index finger, and, on receiving the stimulus to move, proceeded to the designated target, touching it only with the index finger. For two-handed conditions, the subject depressed both home keys with the index fingers and proceeded to hit the respective targets following the onset of the auditory stimulus. All movements from the home keys to the targets were lateral.

Procedure. Eight experimental conditions were used, which varied depending on (a) whether a single- or two-handed movement was required, (b) whether the target was easy or difficult and, (c) whether the movement was of short or long amplitude. The nature of the task was explained to the subjects and the instructions emphasized both speed and accuracy in striking the target(s). When the experimenter was certain that the subject understood the instructions, all eight conditions were performed by the subject. Each condition consisted of 25 trials with a 5-sec intertrial interval and a 1- to 3-sec variable foreperiod between the warning light and the stimulus to move. Only the last 20 trials of each condition were used in the data analysis; the first 5 trials served as familiarization. When each trial block was completed, the
<table>
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Figure 1. Mean reaction time, movement time, and total response times (in msec) for single- and two-handed movements directed away from the midline of the body. For actual dimensions of the targets and their distance from the home keys, refer to the text.
subject was given a 3-min break during which the experimenter re-arranged the targets in preparation for the next movement condition. All movements to targets were monitored by the experimenter. If the subject missed the target or hit the target with anything other than the index finger, that trial was excluded from the data analysis. Furthermore, reaction times greater than 600 msec or less than 90 msec and movement times greater than 600 msec and less than 30 msec were also excluded.

**Design**

A within-subjects design was used with all 11 subjects performing in all experimental conditions, whose order was randomized. From the 20 trials in each condition, mean reaction time, movement time, and total response time were computed for each hand. There were four single-handed and four two-handed conditions, making a total of 12 separate means for each subject and for each dependent variable. Preplanned contrasts using Dunn's procedure (Kirk, 1968, p. 79) were carried out on the means of interest.

**Results and Discussion**

The mean reaction times, movement times, and total response times are shown for each condition in Figure 1. Given the current debate regarding the use of simple versus choice reaction time as a reflection of the time it takes to select and prepare or "program" upcoming motor responses (e.g., Klapp, 1977; Sternberg, Monsell, Knoll, & Wright, 1978), we prefer not to interpret our results within that theoretical framework. Our chief concern was whether subjects initiated and terminated movements simultaneously, especially under conditions where the task demands were different for each hand.

No significant hand differences in reaction time were found (p > .05). More interestingly, subjects appeared to initiate hand movements in paired conditions virtually simultaneously. This is apparent in Figure 1 where the largest difference between left- and right-hand reaction times is 8 msec (9 and 10). Thus, subjects left the home keys together even in the absence of instructions to do so. The average within-subject correlation between left and right hands in paired conditions was also extremely high (range .95 to .97), further supporting the simultaneity of initiation.

As can be seen in Figure 1, single-handed movement times for the easy task (3 and 4) are much faster than their difficult counterparts (1 and 2) as Fitts' Law predicts (p < .05). This effect is also evident when examining two-handed movements (5 and 6 versus 7 and 8, p < .05). Movement times for single- and two-handed movements of the same difficulty are not significantly different (p > .05). However, when the task demands are varied for each hand, movement times for the easy task (9 and 12) are significantly elevated over paired easy conditions (5 and 6), p < .01. Clearly, the difficult task determines movement time in two-handed conditions.

The movement time data in Figure 1 also indicate that two-handed movements of equal difficulty are executed simultaneously (5 versus 6 and 7 versus 8). Furthermore, paired movements of varying difficulty are also executed virtually simultaneously. Movement times to the easy target (9 and 12) are only slightly faster than movement times to the difficult target (10
and 11). In fact, when total response times are considered, this difference (19 msec) is non-significant \((p > .05)\).

The overall error rate across the eight experimental conditions was 8%. These ranged, as expected, from a small error rate in single-hand conditions (6%) to higher errors in two-handed difficult conditions (13%). The majority of these errors was due to the subject's missing the target or failing to strike the target with the designated finger.

The results of Experiment 1 essentially replicated those of the pilot experiment. The reaction time data strongly suggest that subjects initiated two-handed movements at the same time. Furthermore, paired movements to targets of equal or unequal difficulty were terminated simultaneously, as is evident in their corresponding movement times and total response times. Even though the task demands were quite different under combined conditions, the hands appear to perform in a unitary manner. One drawback to this conclusion is that the outcome of Experiment 1 may have arisen as a result of the targets being placed in the subject's peripheral vision. Thus, subjects may simply have attended to or monitored movement to the difficult target, leaving the contralateral hand to perform a subsidiary role. In Experiment 2 we wanted to check whether this was a necessary and sufficient condition for the apparent time dependence between the hands. The way we chose to confront this issue was to have both movements terminate in focal vision. To accomplish this, we simply interchanged targets with home keys so that the former were placed directly in front of the subject.

**EXPERIMENT 2**

**Method**

**Subjects.** The subjects were 12 student volunteers who had not participated in Experiment 1 or the pilot study. One subject's data were lost due to equipment malfunction.

**Apparatus.** The apparatus was similar in design to that used in Experiment 1, the only difference being that the position of the home keys and targets was interchanged. Thus, the targets were now directly in front of the subject and the home keys could be adjusted to different distances from the targets. The task therefore involved flexion primarily of the elbow joint towards the midline of the body. Target dimensions and movement amplitudes were the same as those in the previous experiment.

**Procedure and Design.** The procedures for Experiment 2 were identical to those of Experiment 1, except that subjects received only 20 trials per condition. The first five trials served as familiarization and were not included in the analysis. Preplanned comparisons were carried out on relevant mean reaction times, movement times, and total response times.

**Results and Discussion**

The mean reaction times, movement times, and total response times are shown for each condition in Figure 2. As in Experiment 1, no significant
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<th>Targets</th>
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Figure 2. Mean reaction time, movement time, and total response times (in msec) for single- and two-handed movements directed towards the midline of the body.
differences in reaction time were found (p > .05). The largest difference between the hands was 15 msec (9 and 10), which was not significant. That subjects' hands were leaving the home keys together is further supported by the high within-subject correlation between left and right hands (range .74 to .98).

The data again indicated the expected relationship between single-handed movements for the easy task (3 and 4) and the single-handed movements for the difficult task (1 and 2), with the easy task clearly resulting in faster movement times (p < .01). This effect was also evident in two-handed movements (5 and 6 versus 7 and 8, p < .01). Once again, the two-handed movements of equal difficulty (5 versus 6 and 7 versus 8) were executed simultaneously. As in Experiment 1, the difficult task appears to determine the movement time in two-handed conditions. The slight movement time advantage of the easy task (9 and 12) over the difficult task (10 and 11) in combined conditions disappears when total response time is considered (p > .05). The overall error rate across the eight experimental conditions was 1.8%.

The results of Experiments 1 and 2 revealed identical effects, in that simultaneity of initiation and termination occurred in all combined movement conditions. It should be noted that in both experiments the task involved symmetrical muscle groups resulting in movements in opposite directions. To further examine the generality of the simultaneity effect we employed a task that also involved symmetrical muscle groups, but that required movements in the same direction. Consider the case where the subject must produce two-handed movements of varying difficulty in the forward direction. An opportunity is afforded the subject to terminate the easy task before the difficult one. Thus, if both hands are initiated together and proceed forward at the same rate, the subject could feasibly strike the near target first, and the simultaneity effect would break down.

**EXPERIMENT 3**

**Method**

**Subjects.** The subjects were 12 student volunteers who did not participate in either of the previous studies.

**Apparatus.** The basic model of the apparatus remained consistent with Experiments 1 and 2. However, the equipment was altered so that movements could be made forward in the sagittal plane, rather than laterally. This was accomplished by having two identical pieces of Plexiglas (106 cm long, 7 cm wide, and .8 cm thick), each with a single home key and moveable and interchangeable targets. Target widths and distances from the home keys were the same as those used in Experiments 1 and 2. The two pieces of apparatus were positioned parallel to each other, extending forward from the seated subject. The warning display and auditory stimulus setup was identical to the two previous experiments. The onsets of warning light and stimulus tone were controlled by a PDP 8/A computer, which also collected reaction times, movement times, and total response times.
Procedure and Design

The procedures and design for Experiment 3 were identical to those of Experiment 2, with all subjects performing in all eight experimental conditions in a randomized order.

Results and Discussion

The mean reaction times, movement times, and total response times are shown for each condition in Figure 3. The subjects initiated movements together, as indicated by the null effect of right versus left hand in the paired conditions and the high within-subject correlation (range .82 to .98).

The easy versus difficult task manipulation was effective as indicated by the longer movement times to the far target, both in the single-hand condition (3 and 4 versus 1 and 2, p < .01) and in paired conditions of the same difficulty (5 and 6 versus 7 and 8, p < .01). The difficult task once again exerted a major influence on the movement time in combined conditions as evident in the increase in movement time of the easy hand when the contralateral hand performs the more difficult task. The major finding of simultaneity once again appeared with the slight movement time advantage of the easy task (10 and 11) over the difficult task (9 and 12) being further reduced when one considers total response time (mean difference 14 msec, p > .05). The overall error rate across the eight experimental conditions was 1.0%.

GENERAL DISCUSSION

There is a remarkable consistency in the pattern of results across the three experiments. First, notice that movement times for the so-called difficult task in single-hand conditions are greater than for the easy task. Second, the easy-difficult difference carries over to two-handed movements when the task is the same for each hand. But most interesting is the finding that movement times for paired movements of unequal difficulty are virtually identical. When total response times are considered, any difference in termination between the hands is greatly reduced. This set of findings cannot be attributed to a peripheral vision problem (see Experiment 2), nor to the fact that in Experiments 1 and 2 the hands always move in opposite directions. When subjects are afforded the opportunity to break down the apparent time dependence between the hands in Experiment 3, they do not take it. In all three experiments, then, subjects initiate and terminate symmetrical movements of the hands to different points in space virtually simultaneously. A key issue for the present paper concerns whether the limbs are controlled as separate units in the easy-difficult case or, conversely, whether they are constrained to act as a single unit. More specifically, do the central commands prescribe the details of the intended movements for each hand or, alternatively, are central commands referred to functional groupings of muscles that operate fairly autonomously to produce simultaneity of action?

It seems quite tempting, for example, to interpret the present data in terms of a central program specifying different commands for each limb. The parameter remaining constant in this case—movement duration—might be viewed as "setting the limits" for the commands generated. Indeed, this is not an unreasonable position, for there is ample evidence from reaction time/movement
Figure 3. Mean reaction time, movement time, and total response times (in msec) for single- and two-handed movements in the forward direction.
time studies that duration is a major variable influencing the programming process (Kerr, 1978, for a review). Furthermore, recent neurophysiological data suggest that the duration parameter is centrally preprogrammed (Brooks, 1974; Koslovskaya, Atkin, Horvath, Thomas, & Brooks, 1974). When the location of mechanical stops was altered unbeknownst to monkeys producing rapid alternating elbow movements, they nevertheless maintained movement duration constant. Thus, rather than oscillating between the stops as quickly as possible, they exerted force against the newly placed stops, keeping the originally-learned rhythmic pattern stable.

But a rather different mode of control may be suggested from Bernstein's (1967) original work and subsequent research on activities such as locomotion (see Boylls, 1975; Grillner, 1975; Shik & Orlovsky, 1976, for reviews) and respiration (Gurfinkel', Kots, Pal'tsev, & Fel'dman, 1971). Movements are viewed as centrally programmed, not in terms of individual muscle contractions but rather according to muscle linkages. A linkage is defined as a group of muscles whose activities covary as a result of shared efferent or afferent signals (Boylls, 1975). For example, extensive studies on locomotion in animals reveal that movements are organized in terms of basic flexor and extensor linkages—spinal locomotor automatisms (Shik & Orlovsky, 1976)—involving both proximal and distal joints.

This basic mode of motor organization is revealed in an experiment—somewhat analogous to the present studies—performed by Kulagin and Shik (1970) on mesencephalic cats running on a treadmill at two different speeds. In this situation the movements of the two sides of the body are different just as they are in normal activities such as turning or circling. Although the speeds of symmetrical limbs were obviously different and took the form of a strict alternation pattern, the duration of the step cycle remained constant. This was achieved by lengthening the stance phase and shortening the swing phase on the slower belt, with a concomitant shortening of the stance phase and lengthening of the swing phase on the faster belt. It appears that a low level mechanism is involved in this interaction between the two sides of the body, for an identical result occurs in the spinal animal (Grillner, 1975).

The picture of interlimb coordination that emerges from studies of this type is that the task of central signals is not to prescribe the details of the intended movement but rather to organize functional groupings of muscles—coordinative structures (Easton, 1972; Turvey, 1977)—in a relatively autonomous fashion. Viewed in light of the present experiments, this style of control argues that the brain sets the level of activity in low level automatisms based on the spatial demands of the task, but leaves them to generate the pattern of interlimb coordination seen in simultaneous movements. Indeed, we have data that suggest that in a task where the spatial demands vary on each side, the limbs are constrained to function as a single unit. High-speed cinematographic analysis (200 frames/sec) reveals that the limb moving to the easy target does not hover over the target or "wait" for its difficult counterpart, but moves at an entirely different speed. More importantly, as Figure 4 reveals, the limbs under easy-difficult target conditions reach peak velocity and peak acceleration at practically the same time during the movements. Thus, although the limbs move at different speeds, their velocity and acceleration patterns are nearly perfectly synchronous.
Figure 4. The pattern of displacement, velocity, and acceleration over time for two-handed movements of unequal difficulty obtained from single frame kinematic analysis (frame rate = 200 frames/sec). Over a series of six trials the mean time difference in peak velocities was 9 msec, while the mean difference between peak accelerations was 14 msec for positive acceleration and 4 msec for negative acceleration.
This suggests a strong interaction between the limbs and is not conducive to an independent programming view. The apparently fixed and reproducible interaction between the limbs seen in the present experiments to produce simultaneity of action may be viewed as the discovery of a coordinative structure or muscle linkage, a goal that has motivated much of the Russian work on motor control (e.g., Gurfein & et al., 1977). The notion that motor coordination involves a reduction of the degrees of freedom of the motor apparatus, first advanced by Bernstein (1967) and lately extended by Turvey (1977), requires the existence of low level coordinative structures that govern the interaction between limbs. Such collectives are not necessarily prefabricated, as Easton (1972) has argued in the case of reflexes. Rather, they are functional and may be marshalled temporarily and expressly for the purpose of accomplishing a particular behavioral goal.

This perspective on coordination raises numerous theoretical issues. Boylls (1975), for example, has discussed how the deployment of coordinative structures is parameterized. At one level is the structural prescription defined as a set of qualitative ratios of activities in the linked muscles, independent of absolute activity levels. On the other hand, the metrical prescription of a coordinative structure specifies the absolute level of activity in linked muscles. The latter may be viewed as a scalar quantity that multiplies the activities of all muscles in the linkage. Boylls argues, with respect to the anterior lobe of the cerebellum, that structural prescriptions are tuned by adjusting the relative amounts of activity distributed among descending tracts from the cerebellum, while metrical prescriptions are governed by the absolute activity levels in those tracts. This view receives strong support from Orlovskii's (1972) data showing that cerebellar stimulation during cat locomotion affects only the magnitude of muscle contraction, leaving unchanged both the period duration and the timings of periods relative to the cat cycle. This may be the principal characteristic of a coordinative structure. Namely, when a group of muscles is constrained to act as a unit, some temporal relationship is preserved invariantly over changes in the magnitude of activity (Turvey, Shaw, & Mace, 1978).

Our data on two-handed movements fit this theoretical perspective rather well. When the movement kinematics are examined, it is quite obvious that the magnitude of forces produced for each hand is different (see Figure 4). Thus, the equilibrium points for each hand may be preset and the neural output specified accordingly in terms of the magnitude of forces required (Bizzi & Politi, in press; Kelso, 1977). However, the underlying temporal structure remains invariant between the hands such that they preserve a synchronous relationship to each other. Hence, the metrical prescription (specified by the spatial parameters) is modulated for each hand, yet the structural prescription (the relative timing between the hands) remains invariant.

In conclusion, the present experiments represent an initial attack on a problem that has been largely ignored by motor behavior researchers, namely interlimb coordination. Consequently, apart from some recent theorizing of a preliminary nature (Turvey, 1977; Fowler & Turvey, 1978) formal theoretical development has been sadly lacking. We feel that the present behavioral paradigm, especially when combined with movement analysis techniques, has broad potential for examining coordination issues. Our data suggest that when the motor system is faced with controlling multiple degrees of freedom, as in
the two-handed task, it solves the problem optimally by constraining the limb musculature to act as a single unit. If this is so, then variables designed to influence one limb’s moving to a spatial target (such as slowing the limb down or requiring a change in the limb’s angle of projection) should have concomitant modulatory effects on the other limb. Of course, we do not claim that the performer cannot break down these restraints with practice. Many motor tasks require the hands to perform in an independent rather than tightly coupled manner. In the broader perspective, therefore, highly skilled performance might be viewed as a release from the type of temporal invariance exhibited in these experiments.

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FOOTNOTES

1A favorite example is the difficulty an individual often encounters when attempting to rub the stomach and pat the head at the same time.

2In fact we were later to find out, via high-speed cinematographical techniques, that the hand performing the easy task did not "wait" for its more difficult counterpart, but rather moved at an entirely different velocity (see Figure 4).

3This potentially confounding problem was raised by John Morton at a preliminary presentation of the data to the Medical Research Council, Applied Psychology Unit, Cambridge, England, to whom we are grateful.

4The stance or support phase is the interval in the step cycle during which the foot is in contact with the ground. The swing or transfer phase refers to the period of limb retrieval for the next step.