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The Locus of Visual–Motor Learning at the Task or Manipulator Level: Implications From Intermanual Transfer

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To assess the functional locus of visual–motor learning, the computational concepts of "task level" programming (determination of the trajectory of a hand during arm reaching in the Cartesian coordinates) and "manipulator level" programming (determination of the joint coordinates) was adopted. Because the former is likely to be hand nonspecific and the latter is hand specific, it is assumed that learning at the task level should be transferred to the unpracticed hand, whereas that at the manipulator level it should not. Under this assumption, the paradigm of intermanual transfer was used in an aiming task under rotated visual feedback. Nearly 100% intermanual transfer from the practiced hand to the unpracticed hand in the performance time of aiming was found, concluding that the locus of visual–motor learning should be at the task level rather than at the manipulator level.

The process whereby some experience in one activity leads to an improved performance in another is referred to as *generalization.* Human motor learning is characterized by its great generalization ability, in which the experience gained from a particular posture or movement can improve another posture or movement. A good example of the generalization of learned movements is the phenomenon of intermanual transfer, in which training given to one hand will carry over to the other hand. We examined intermanual transfer to assess the functional locus of visual–motor learning. We interpret the data in the context of a computational framework taken from the robotics field.

Intermanual Transfer in Visual–Motor Learning

The issue of intermanual transfer is not entirely new in the visual–motor learning literature, having been studied since the 1800s. The majority of studies of intermanual transfer have concerned learning after the rearrangement of visual feedback by a prism.

Harris (1963) focused on the prism's aftereffect. After viewing pointing by his or her own hand through wedge prisms, the observer's pointing at auditory as well as visual targets was affected by the prism. However, performance with the other hand was unaffected; that is, there was no intermanual transfer. From this and other evidence, Harris concluded that the change during prism adaptation was in the felt position of the hand rather than in its seen position.

Cohen (1967) reported that the availability of visual feedback affects intermanual transfer. Some observers had an opportunity to view their hands continuously through prisms. Other observers rapidly introduced their hands into a prismatic field of vision as they swiftly reached for the target, so they could view their hands through the prisms only near the terminal point of the reaching movement. Cohen labeled the former experimental condition as *continuous* visual feedback and the latter as *terminal* visual feedback. He reported that intermanual transfer occurs under terminal visual feedback and does not occur under continuous visual feedback.

Later, Taub and Goldberg (1973) found that intermanual transfer of a prism's aftereffect occurred under spaced (distributed) training but not under massed training. Cohen (1973) further examined the effect of massed and spaced training under continuous visual feedback and terminal visual feedback. He reported that for terminal visual feedback, the magnitude of intermanual transfer significantly decreased with increasing response rate (with massed training), whereas for continuous visual feedback, no significant intermanual transfer resulted with any rate of response.

Another method for studying visual–motor learning has been mirror drawing, in which a relatively high degree of intermanual transfer has been reported (75% transfer in

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saving time in Cook, 1933; about 30% transfer in the number of errors in Bray, 1928).

Thus, the degree of intermanual transfer varies, depending on various learning conditions such as the availability of visual feedback, the training schedule, and the nature of the visual–motor rearrangement. Even though intermanual transfer has been studied in psychology for many years, not much communication has occurred across computational and behavioral studies, mostly because of the lack of a common theoretical framework and terminology. We adopted the concepts of "task level" programming and "manipulator level" programming suggested by Saltzman (1979) and Hollerbach (1990), which we explain in the next section. These concepts are useful in specifying the locus of visual–motor learning because they relate intermanual transfer to theoretical models.

Motor Programming at Task Level and Manipulator Level

Saltzman (1979) studied problems in planning sensory–motor actions. He viewed the action plan as a complex structure with many hierarchical levels (from conceptual to muscle). One important fact he emphasized was that the specific environmental trajectory of a transported object depends on the effector system used in a given task situation. Therefore, he divided a part of the action plan structure into three substages: (a) planning in the effector–nonspecific environmental space, (b) effector system selection, and (c) planning in the effector–specific environment space. Saltzman (1987) has extended his distinctions between task and manipulator levels of motor control and has developed a "task-dynamic" approach to skilled movements of multiple degree-of-freedom effector systems within a functionally defined dynamical framework.

The distinction between nonspecific and specific effector levels of sensory-motor representation was also advocated by Hollerbach (1990). He proposed that two different levels of programming should be distinguished in the planning and controlling of biological or artificial hand movements: the task level and the manipulator level.

Let us consider a robot having eyes, arms, and hands that intend to reach for a cup in front of it. This robot must first identify the location of the cup with its eyes and determine the trajectory from its hand (current position) to the cup in "Cartesian space," or the x–y coordinates, which are either based on visual representation or are fixed on a given point in the external world. This planning of the trajectory in Cartesian space is called *task level* programming. This programming level is useless unless it is translated into joint angles and torque. This second stage is called *manipulator level* programming. General algorithms for translating Cartesian coordinates into joint coordinates have been successfully implemented. Soechting and Terzuolo (1986) proposed an algorithm that specifies the angular motion at the shoulder and elbow joints.

We explain the idea of task level and manipulator level programming more precisely in terms of intermanual transfer. For simplicity, we first consider the kinematics of a human arm confined to a horizontal plane (see Figure 1; modified from Hollerbach, 1990). In this plane, the left and right shoulder joints have a single degree of freedom measured by angles $\theta l1$ and $\theta r1$. Similarly each elbow joint has a degree of freedom measured by $\theta l2$ and $\theta r2$. Thus, only the shoulder joints and elbow joints are allowed to move. The trajectory of the distal end of the forearm is referred to as position $[x(t), y(t)]$ in Cartesian coordinates (i.e., the task level programming space). When the point $[x(t), y(t)]$ is referred to at the manipulator level, however, its reference can be entirely different depending on whether the left or right arm is used; either $[\theta l1(t), \theta l2(t)]$ or $[\theta r1(t), \theta r2(t)]$. These kinematics terms must be translated further into torque terms at each joint, that is, $[\tau l1(t), \tau l2(t)]$ or $[\tau r1(t), \tau r2(t)]$. As is obvious from this simple framework, the task level coordinates are shared commonly between the left

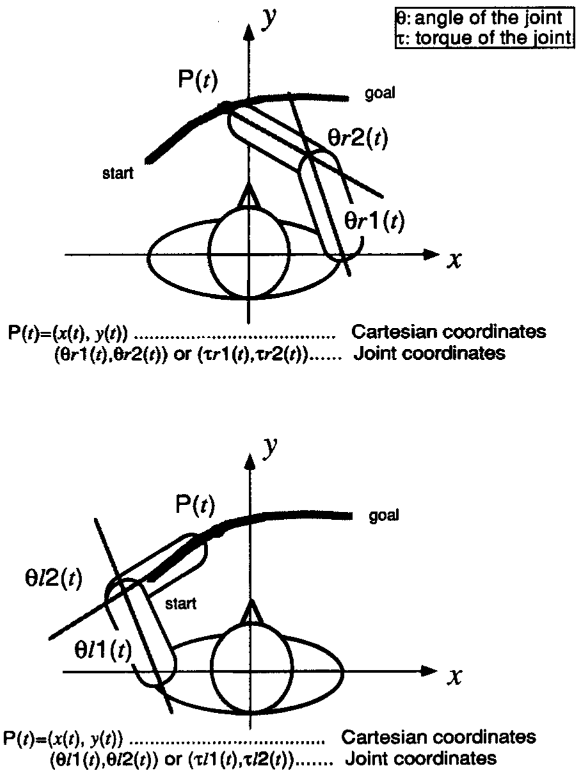

Figure 1. A simplified model of the human arm (From *Visual Cognition and Action: An Invitation to Cognitive Science*, p. 160, by D. N. Osherson, S. M. Kosslyn, & J. M. Hollerbach, Eds., 1990, Cambridge, MA: MIT Press. Copyright 1990 by MIT Press. Adapted with permission). Each shoulder joint has a single degree of freedom measured by angle $\theta l1$ or $\theta r1$, and each elbow joint has a degree of freedom measured by angle $\theta l2$, or $\theta r2$. The end points of each arm [P(t)] on the trajectory from the start to the goal at time (t) can be located by Cartesian coordinates $[x(t), y(t)]$. For the purpose of generating motor commands, however, they are located by joint coordinates $[\theta r1(t), \theta r2(t)]$ for the right hand, and $[\theta l1(t), \theta l2(t)]$ for the left hand. In this case, the trajectory is represented in terms of joint torques, that is, $[\tau r1(t), \tau r2(t)]$ for the right hand, and $[\tau l1(t), \tau l2(t)]$ for the left hand.

hand's and the right hand's control systems, whereas the joint coordinates for one hand are independent of those for the other.[1]

Figure 2 shows a schematic flowchart of arm control under visual guidance, illustrating the typical framework of the computational approach. Human motor control may be viewed as a series of transformations from a specified behavioral objective to a plan for the desired mechanical output of the motor apparatus and finally to a pattern including the activation of muscles (Kawato, Furukawa, & Suzuki, 1987). Information on the position of the target is obtained through the visual system. At the trajectory planning stage, trajectories are thought to be planned in the visual–spatial coordinates and determined independent of the hand. Therefore, this stage belongs to the task level. The desired trajectory must be translated into joint angle (inverse kinematics) terms. Motor commands must be generated to coordinate the activity of many muscles (inverse dynamics). After the inverse kinematics stage, the parameters specifying the desired trajectory are hand-specific joint angles and torque (activities of muscles). Consequently, these stages are the manipulator level.

Goal of This Research and How to Achieve It

Our reasoning to reveal the functional locus of visual–motor learning is as follows:

1. If learning occurs at the manipulator level, intermanual transfer will not be observed because the critical learning will be different at the manipulator level, depending on whether the right or left hand is to be used. Consequently, functional changes at the manipulator level will not help the performance of the other hand.
2. If learning occurs at the task level, perfect intermanual transfer will be observed. At this level, the trajectories of the hand are represented by Cartesian coordinates, which are more likely to be shared by the left-hand and right-hand systems.
3. If learning occurs at both the task and manipulator levels, intermediate intermanual transfer will be observed.

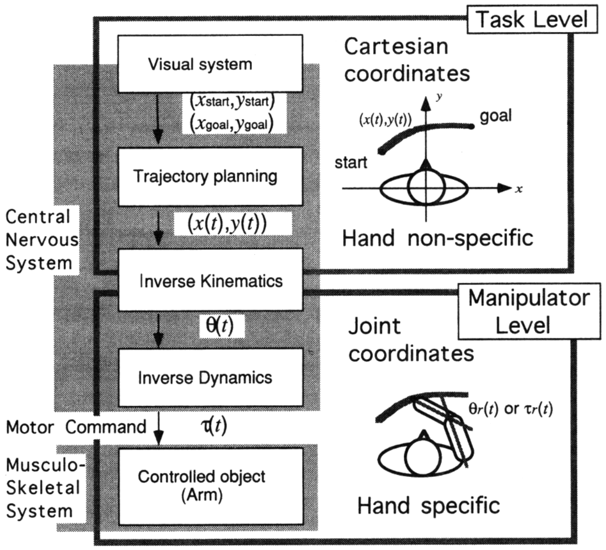

Figure 2. Schematized diagram of visual–motor control illustrating different functional levels. Arrows indicate the flow of information.

The ideal visual–motor task for this purpose is one that participants have seldom encountered in daily life and the difficulty of which is suitable for the study of intermanual transfer. If the task is too difficult or too easy for the participants to learn, the effects of learning cannot be measured. Cunningham (1989) used an aiming task under visual feedback that was rotated through various angles from 0° to 180°. She found that the aiming task was relatively easy when the rotation was 0° and 180° but more difficult when it was 90° to 120°. The difficulty of the task increased from 0° to 90° and decreased from 120° to 180° monotonically. Many other researchers have used tasks under top–bottom inversion and left–right reversal of visual feedback using optical equipment (wedge prisms or mirrors) or a television monitor (Smith & Smith, 1962), but our pilot observations suggest that 90° rotations are more difficult than inversion or reversal; with practice, however, the participants can dramatically improve their performance. Thus, we adopted an aiming task with 90° rotation of visual feedback.

However, there is a critical methodological difference between Cunningham's (1989) experiment and ours. In her experiment, the participants' task was to acquire the target using as straight a path as possible without emphasis on speed. Thus, the performance of each participant was eval-

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[1] We consider the Cartesian and the polar coordinates only as seemingly suitable coordinate systems for task level and manipulator level programming, respectively. Obviously, these are not the only choices. Different types of coordinate systems can be used at each level. In fact, it has been a point of contention whether the visual representation of the external world is in Cartesian or polar coordinates. In this article, we assume the Cartesian space as many other investigators (e.g., Hollerbach, 1990; Kuperstein, 1988). Even with the same type of coordinate system, however, the reference point of the coordinate system could be another point of debate. Cartesian (or polar) coordinates fixed on a reference point in the external world are the most plausible candidate coordinates for the task level programming. However, we can also think of Cartesian (or polar) coordinate systems that are not fixed on a reference point in the external world but on a body part; for example, the retina, the head (Zipser & Andersen, 1988), the body trunk, and so forth. Similar arguments could apply to the coordinates used for manipulator level programming. Indeed, the central nervous system might use multiple Cartesian or polar coordinates, each referenced to a different origin (i.e., the right and the left shoulders; Soechting & Flanders, 1989). The planning in these coordinates can also be called *manipulator level* programming as far as they are effector (arm) specific. Thus, in short, the distinction between the sorts (Cartesian or polar) or among the reference points of coordinate systems does not necessarily correspond to the distinction between the task and manipulator levels. Even though we use Cartesian and joint coordinates to represent effector nonspecific and effector specific coordinates, respectively, the only distinction critical to the logic underlying our experiments is whether the coordinates are effector specific or effector nonspecific.

uated by studying the redundancy of the trajectory (Cunningham, 1989), and the discussion mainly focused on the spatial properties of movements (Cunningham & Vardi, 1990). In our research, on the other hand, we are interested in how the temporal (e.g., reaction time, movement time, and so on) and the spatiotemporal (e.g., velocity, acceleration, etc.) characteristics of each participant's performance changed with practice as well as how spatial characteristics would change. Therefore, in addition to Cunningham's procedure, we required our participants to acquire the target as rapidly as possible so that the temporal and spatiotemporal characteristics would change. Thus, the effect of learning was evaluated by the performance time (from the onset of a starting signal to the time when the participant acquired the target) rather than the redundancy of the trajectory. This procedural difference will be discussed later in the General Discussion.

In Experiment 1, the difficulty of aiming as a function of the rotational angle of visual rearrangement was reexamined. In Experiment 2, extensive training was given to each participant, and the process of learning was examined under the most difficult rotation (i.e., 90°). Changes in the velocity profile were also analyzed both qualitatively and quantitatively. In Experiment 3, the degree of intermanual transfer was measured under our assumption that nearly 100% intermanual transfer would indicate learning at the task level, whereas nearly 0% transfer would indicate learning at the manipulator level.

General Method

Apparatus and Stimuli

For all experiments, we used a color CRT monitor and a touch panel connected to a personal computer (NEC PC-98 VM) for the aiming task. The background color of the CRT screen was black. The start zone was a white circle 5 mm in diameter (visual angle of 11′) and located at the center of the CRT screen. The targets were also white circles 5 mm in diameter (visual angle of approximately 0.25′) and located 7.5 cm (visual angle of approximately 5.7°) from the center of the start zone (see Figure 3A for details). There were four possible target locations (on the diagonals) in Experiment 1 and eight possible locations (every 45°) in Experiments 2 and 3. The cursor, which was a white circle 0.5 mm in diameter, was movable. The circles representing the targets, the start zone, and the cursor were of equal luminance (16.1 cd/m^2).

Each participant moved the cursor using the touch panel placed horizontally in front of them. The participant pushed the panel with the tip of his or her own index finger and moved on the panel without removing the finger from it so that the movement could be recorded through the panel. The participant wore a plastic cap on the tip of his or her index finger to prevent friction between the skin and the surface of the touch panel and to keep the area of contact constant. The participants were not allowed to touch the panel with any other body parts. The visual–motor gain was 1.0 (i.e., moving the finger for 1 cm caused the cursor to move 1 cm on the CRT).

Figure 3B illustrates the apparatus. An occluder was placed above the touch panel and the participant's hand to avoid direct visual feedback. The CRT's display surface was slanted 30° from the horizontal plane toward the participant for easy observation. The distance from the center of the CRT screen to the participant's eyes was about 75 cm. The room was moderately dark.

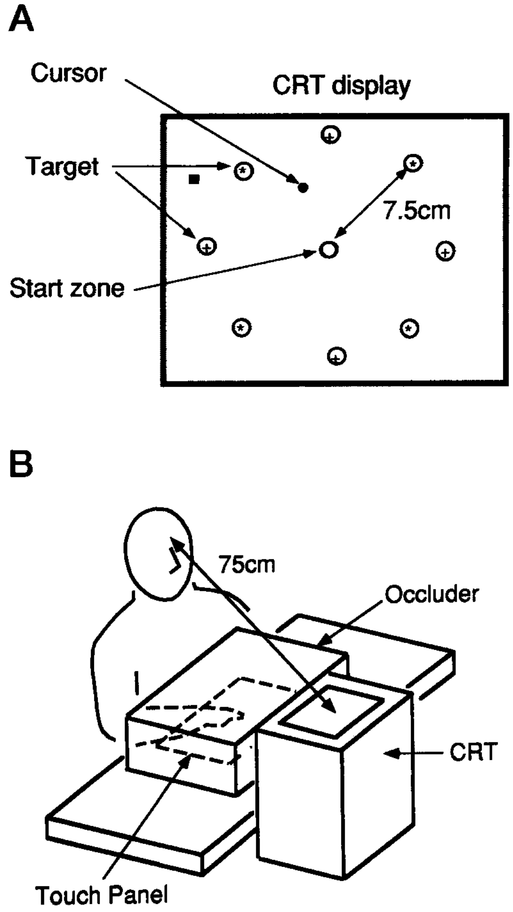

Figure 3. A: The locations of the starting point and targets on the CRT screen. Targets indicated by a plus sign (+) were used in Experiment 1, whereas targets with an asterisk (*) and a plus sign (+) were used in Experiments 2 and 3. B: The experimental setup.

Procedure

Each trial consisted of the following sequence: The participant touched the center of the touch panel with the plastic cap, which then turned on the start zone at the center of the CRT screen. The start zone remained there until the cursor arrived at the target. After 1 s, a cueing tone (click) was generated by the computer. At the same time, a target appeared at one of four (in Experiment 1) or eight (in Experiments 2 and 3) possible locations and a cursor appeared at the center of the target zone. The cueing tone and appearance of the target and cursor signaled the beginning of the trial. The task for the participant was to move the cursor from the start zone to the target as rapidly as possible using the touch panel. Participants were also instructed to make their paths from the start zone to the target as straight as possible. The trial was terminated when the cursor arrived at the target circle.

Data Acquisition

The trajectory of each participant's hand was recorded spatiotemporally through the touch panel. The positions of the tip of the participant's index finger on the surface of the touch panel were sampled and stored on-line at 65-ms intervals. The spatiotemporal recordings of the participant's performances in the visual–motor task, as pioneered by Hay (1979) in his prism adaptation study, helped us to reveal changes of quality in the movements with practice.

Experiment 1

Method

Participants. Three adult men (age 22–27 years) and 2 adult women (age 22–25 years) volunteered as participants. All volunteers were right handed and naive as to the purpose of the experiment.

Procedure. An experimental session consisted of 140 trials (7 angles of transformation × 4 locations of the target × 5 trials) and lasted about 40 min. Angular conditions were randomized in each session for each participant. Figure 4 illustrates some examples of the angles of transformation used in this experiment. Under the 0° condition, the moving direction of the participant's finger tip and that of the cursor on the CRT display were identical, but under the other conditions the angular discrepancy was varied. The seven angles of rotational transformation used in Experiment 1 were clockwise rotations of the touch panel by 0°, 30°, 60°, 90°, 120°, 150°, and 180°. These rotational transformations were calculated by computer in real time.

The performance time (PT; from the onset of the target, or the starting signal, to the time when the cursor arrived at the target) was measured as an indicator of the difficulty of the task. The PT consists of the reaction time (RT; from the onset of the target to the beginning of movement by the participant) and movement time (MT; from the beginning of movement by the participant to the time when the cursor arrives at the target).

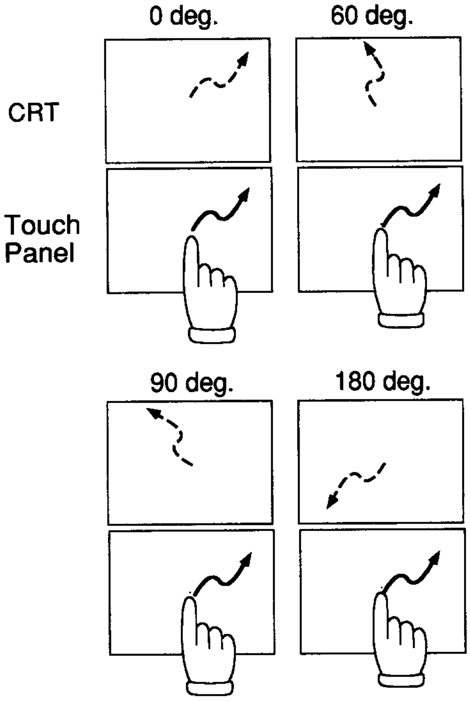

Figure 4. Examples of the rearrangement of visual feedback (0°, 60°, 90°, and 180°). The solid arrows indicate the direction in which the participants moved their finger on the touch panel; the dashed arrows indicate the direction of the resulting movement of the cursor on the CRT display.

Results and Discussion

In Figure 5, the PT of each participant is plotted as a function of the angular rotation in each graph. Curves with open circles indicate the mean of the PTs and curves with closed circles indicate the standard deviation. All participants showed the same tendency in that the means and deviations of the PTs were smaller at 0° and 180° of rotation and larger at 90° and 120°. They increased from 0° to 90° and decreased from 120° and 180°. We applied a 7 (angle of transformation) × 4 (target location) analysis of variance (ANOVA), with repeated measures on all factors. The main effect of the angle of transformation was significant, $F(6, 24) = 3.37$, $p < .025$, whereas the main effect of the target location and the interaction were not significant, $F(3, 12) = .16$ and $F(18, 72) = .53$, respectively. Post hoc comparisons showed significant differences for PTs at 90° versus any degree except 120°, and PTs at 120° versus any degree except 90° (Tukey's honestly significant difference multiple comparisons, $p < .05$). We also applied these analyses to logged PTs and the results turned out to be very similar.

These results are consistent with those of Cunningham (1989) who also found that aiming tasks under transformations of 90° and 120° are most difficult. According to her, movement directions are represented as "bi-directional" vectors in the visual–motor maps. For 180° of rotation, both the direction of the target, which is given visually, and the direction of the actual movement are the same bidirectional vectors, so there is no differences between them except for the sign. For rotations of other degrees, however, there is some difference between the direction of the target and the direction of the actual movement, the difference being largest in a transformation of near 90°.

Cunningham's (1989) theory seems to explain why 90° is the most difficult, but it does not have specific implications for visual–motor learning. We examine the process of visual–motor learning under rotated visual feedback. First, we examine whether learning occurs at all and, if so, how rapidly it occurs under the most difficult condition of rotated visual feedback, that is, 90° rotational transformation.

Experiment 2

Method

Participants. Four right-handed adults who were naive to the purpose of this experiment (2 men, age 18–22 years and 2 women, age 18–20 years) volunteered. Two participants were required to use the right (preferred) hand and the other 2 participants were required to use the left (nonpreferred) hand.

Procedure. An experimental session consisted of 12 blocks of trials and lasted about 40 min. There was no break between trials. Each block consisted of 10 trials. In each block eight targets (see the General Method section and Figure 3a) appeared once or twice

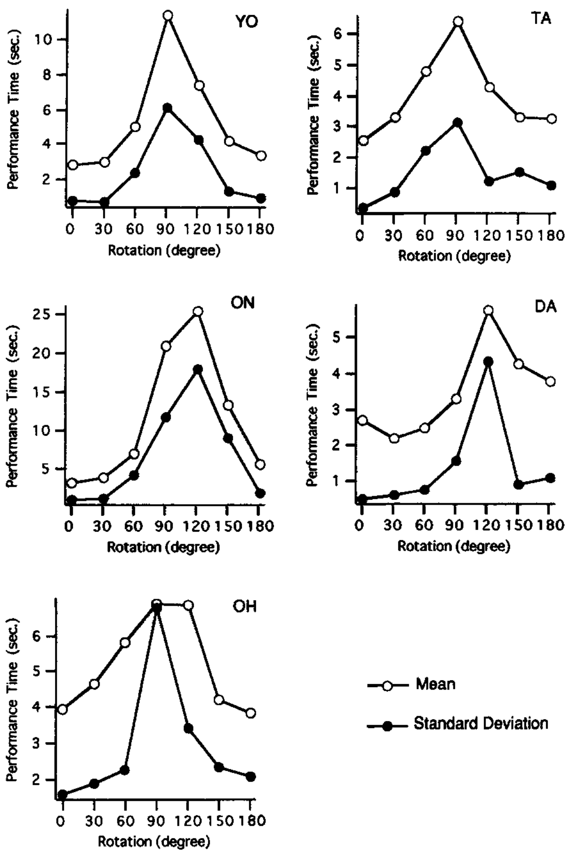

Figure 5. Performance time of each participant (Y.O., T.A., O.N., D.A., and O.H.) plotted as a function of the angular rotation of visual feedback.

in semirandom order under the constraint that the first target of a new block should be different from the last target of the previous block. The angle of rotational transformation was always 90°. We informed the participants of the angle of rotation before starting the experiment.

Results

Performance time, reaction time, and movement time. In Figure 6, the mean PT and RT of each block are plotted separately for each of the four participants. To investigate the global decreasing trend, we pooled the PTs of two successive blocks and carried out a one-way repeated measures ANOVA across pooled blocks ("groups") of trials. This revealed a significant effect of the trial group, $F(5, 15) = 14.11$, $p < .005$. Post hoc comparisons showed a significant difference for the first group versus each of the others, and the last group versus any others except the fourth or fifth ($p < .001$). A trend analysis (Keppel, 1991) on the groups showed that the linear and quadratic components were significant, $F(1, 471) = 147.12$, $p < .0001$; $F(1, 471) = 47.79$, $p < .0001$, respectively. The linear and quadratic components accounted for 93.4% of the between-groups variation. These results suggest that the PT decreases linearly across blocks and that the quadratic component reflects a ceiling effect.

Unlike in Experiment 1, the angle of transformation was constant, and each participant knew it; as a result, the participant could predict the correct direction immediately after the onset of the target without moving his or her hand. Thus, the RT as well as the PT were expected to decrease with practice. We measured the RT by detecting the latency at which the tangential velocity of the cursor exceeded an arbitrary threshold of 8.3 mm/s for the first time after the onset of the target.[2] As shown in Figure 6, the RT decreased with increasing number of blocks. We carried out a one-way repeated measures ANOVA on the RT data in the same way as on the PTs. The effect of group was significant, $F(5, 15) = 14.38$, $p < .005$. Post hoc comparisons showed a significant difference for the first group versus any other, and the last group versus any other group except the fourth or fifth ($p < .05$ level).

As indicated by an arrow in Figure 6 for participant F.U., the MT corresponds to the vertical difference between the PT and RT curves. The MT also decreased across blocks. This was confirmed statistically by a one-way repeated measures ANOVA on the MT data. It revealed that effect of trial group was significant, $F(5, 15) = 13.66$, $p < .005$. Post hoc comparisons showed a significant difference for the first versus other groups and the last versus other groups except the fourth and fifth ($p < .05$ level).

Figure 6 shows that the decline in MT is steeper than that in RT except for participant K.A. We fit the mean RT and MT in each block to a line using the least squares method for each of the 4 participants. The slopes of the MT lines were −.21 (O.S.), −.24 (F.U.), −.21 (A.B.), and −.04 (K.A.), whereas those of the RT lines were −.03 (O.S.), −.07 (F.U.), −.02 (A.B.), and −.04 (K.A.). The slopes of the MT line were much steeper than those of the RT except for those of the participant K.A. Thus, the decline in the PT can be attributed largely to the decline in the MT. In the case of K.A., the initial performance was fairly good compared with that of the other 3 participants, and possibly for this reason, the effect of learning was less prominent.

Trajectories. Figure 7 shows the typical trajectories of 1 participant (F.U.) in the first (Trials 1–4) and the last (Trials 117–120) stages of learning. In the first stage, the trajectories are curved or bent in many places. This indicates that the participant frequently corrected her movement using visual feedback. In the last stage of learning, however, the trajectories are almost linear and the recorded points are sparser.

Velocity profiles. We analyzed the spatiotemporal recordings of each participant's performance using methods similar to Morasso's (1981) and Cunningham and Vardi's (1990). We obtained the instantaneous tangential velocities of the tip of the index finger by calculating the distance that it traveled during each 65-ms interval; we smoothed the data using a 5-point moving average window. Figure 8 shows the instantaneous velocity against time (velocity profile) for

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[2] This value was chosen because it was the lowest velocity value that could be detected with our apparatus.

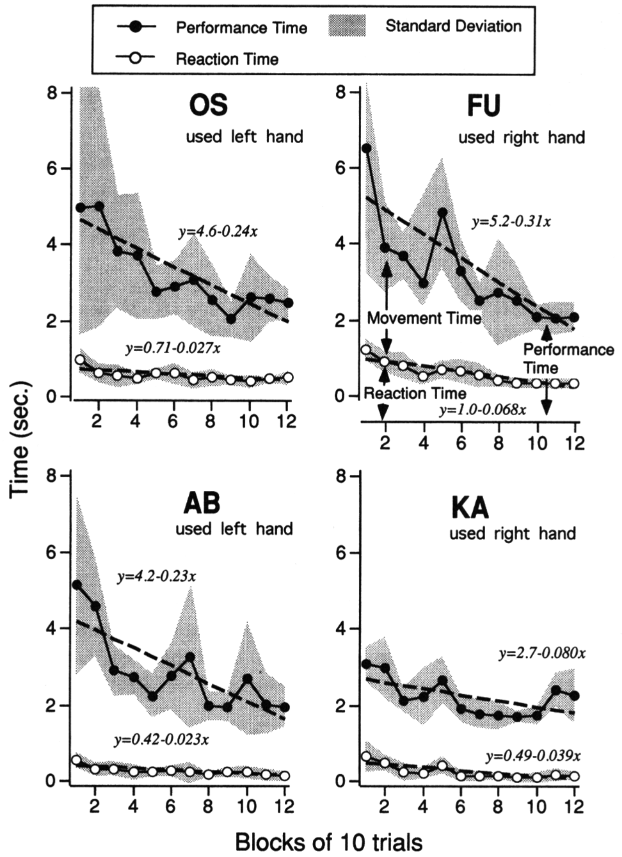

Figure 6. Learning profiles of participants O.S., F.U., A.B., and K.A. The performance time and reaction time for each participant are plotted in each graph. One block consisted of 10 trials. Participants F.U. and K.A. used their right (preferred) hand, whereas O.S. and A.B. used their left (nonpreferred) hand. Dashed lines indicate the best fitting lines by the least squares method. The vertical arrows in the top-right graph indicate performance time, movement time, and reaction time.

each participant. The velocity profiles obtained in four successive trials in the first (Trials 1–4), the middle (Trials 58–61), or the last (Trials 117–120) stage of learning were superimposed in each graph so that their spatiotemporal characteristics and their changes owed to learning became more prominent. In the first stage of learning, the velocity profiles had multiple peaks of various amplitudes, then became increasingly smooth, and finally took on a single-peak, bell-shaped appearance. Occasionally, a participant could arrive at the target in the last stage of learning without a decrease in the velocity; therefore, some bell-shaped velocity profiles terminated before or immediately after the peaks and lacked a tail. The number of peaks and valleys contained in the velocity profiles decreased and the profiles became smoother and more bell shaped with practice.

Discussion

These results indicate that PT decreased with practice; at the same time the quality of movements seemed to have changed as well. This is reminiscent of Woodworth's distinction (as cited in Flowers, 1975) between two components in voluntary movements in an aiming task: There is an "initial impulse phase" that is followed by a series of "secondary adjustments" made to attain the final target position. The first component is a fast, preprogrammed movement that brings the hand into the general area of the target. The second component comprises a number of adjustments. In this latter phase, movements are constantly monitored and adjusted according to sensory information. The first component, the "initial impulse phase" in Woodworth's terminology, can be called a *ballistic* movement, and the second "current control" component can be called a *corrective* movement (Flowers, 1975). Many investigators have noted that the velocity profiles of simple and fast arm movements are approximately single, bell-shaped curves (Abend, Bizzi, & Morasso, 1982; Atkeson & Hollerbach, 1985; Beggs & Howarth, 1972; Kelso, Southard, & Good-

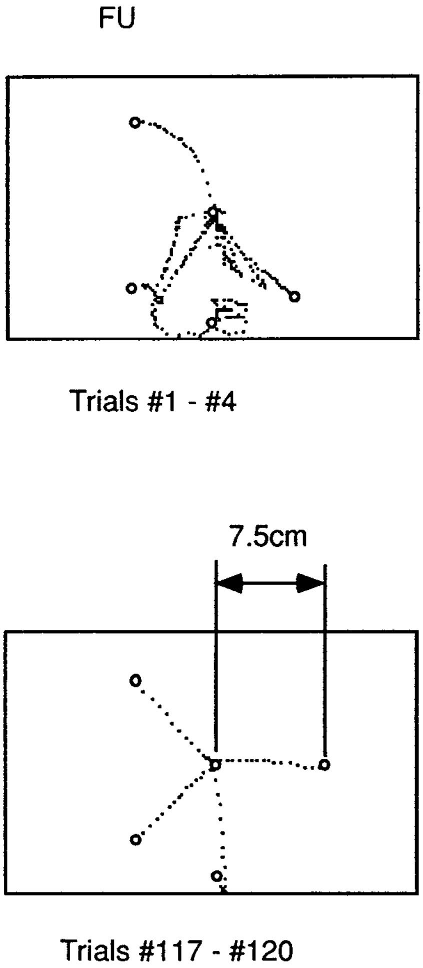

Figure 7. The trajectories of one typical participant (F.U.) in the first (Trials 1–4) and the last (Trials 117–120) stages of learning. Each rectangle indicates a frame of the touch panel that was positioned relative to the participant in this orientation. The center circle indicates the starting zone and the four circles around it indicate the targets.

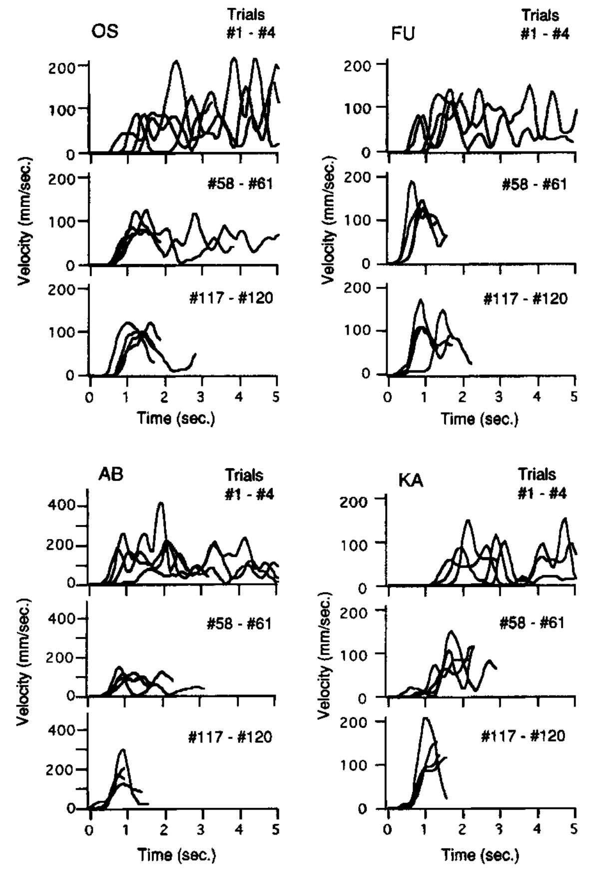

Figure 8. The instantaneous velocity against time (velocity profile) for participants O.S., F.U., A.B., and K.A. Velocity profiles obtained in four successive trials in the first (Trials 1–4), the middle (Trials 58–61), and the last (Trials 117–120) stages of learning were superimposed in one graph.

man, 1979). Many preprogramming models of movement (e.g., Flash & Hogan, 1985; Uno, Kawato, & Suzuki, 1989) predict this bell-shaped profile of the single peak. Thus, it can also be regarded as a critical indicator of a ballistic movement.

When I compared the velocity profiles of the three blocks, those of the first block consisted of many peaks and valleys, and this indicated that the participants made many corrective movements until they arrived at the target because of the crudeness and inaccuracy of the fast, preprogrammed ballistic movement. Thus, at the first stage of learning, the movement can be described as a series of "corrective" movements. However, as the number of trials increased, the accuracy of the ballistic movement improved and the participants no longer needed to correct their movement as often as before. After the onset of the target, the participants determined the required directions, preprogrammed the movement without visual feedback, and arrived at the target without many corrective movements.

We have suggested thus far that learning occurred in the most difficult condition (90° rotation of visual feedback) and that the quality of movements changed (from corrective to ballistic movements) as the learning proceeded. On the basis of these findings, we proceed to the main question of the current study: Where is the locus of the visual–motor learning? We address this question by looking for intermanual transfer.

Experiment 3

Method

Participants. Eighteen adults (12 men, age 18–28 years, and 6 women, age 18–26 years) volunteered. All of them were right-handed and naive as to the purpose of the experiment. They were divided into two groups randomly (Group A and Group B, see below).

Procedure. We adopted the pretest–posttest paradigm to assess intermanual transfer. There were three sessions in Experiment 3. The time interval between any two sessions was shorter than 10 s. The first session was a pretest using one hand. The participants who belonged to Group A used the left (i.e., nonpreferred) hand, whereas those who belonged to Group B used the right (i.e., preferred) hand in this session. The second session was a training session using the other hand. The participants in Group A used their right hand and those in Group B used their left hand. The third session was a posttest session using the same hand used in the pretest session.

The first pretest session (and the third posttest session) consisted of 10 trials of the aiming task under a rotation of 90° (i.e., the same task as that in Experiment 2). The size of these two sessions (10 trials) was chosen as a compromise between two pragmatic constraints. On one hand, it had to be brief enough to minimize the learning within these sessions; on the other hand, it had to be long enough to eliminate noise factors so that the participants' performance could be assessed reliably.

In the second training session, the participants had to perform this task with the other hand repeatedly until they reached the criterion that the PT of each trial be less than 3 s in 9 of 10 successive trials. The mean number of trials required to reach the criterion was 97.6 (range = 29–219) for the participants of Group A and 86.9 (range = 36–143) for those of Group B. The location of targets was determined pseudorandomly in the same manner as in Experiment 2. The rotational angle of visual feedback had been fixed at 90° throughout the three sessions.

Data analysis. We compared the PTs of (A) the 10 trials in the pretest (one hand), (B) the first 10 trials at the beginning of training, (C) the last 10 trials at the end of training (the other hand), and (D) the 10 trials in the posttest, as indicated in Figure 9. If intermanual transfer is complete, the value of (D) will equal that of (C). In this case, we can conclude that the motor skill learned by one hand during the training session was entirely available for the control of the other hand. Thus, 100% intermanual transfer would be characterized as an L-shaped profile as shown in the left column of Figure 9.

If intermanual transfer is nearly 0%, however, the value of (D) will equal that of (A). Unlike in the previous case, the motor skill learned by one hand is not available for the control of the other hand, and the participant must perform the posttest trials using the untrained hand as in the pretest. Thus, 0% intermanual transfer can be characterized as a V-shaped profile as shown in the right column of Figure 9.

To estimate the degree of intermanual transfer (IMT) quantitatively, we postulated the IMT index to be

$$\mathrm{IMT} = (\mathrm{A} - \mathrm{D})/(\mathrm{B} - \mathrm{C}). \qquad (1)$$

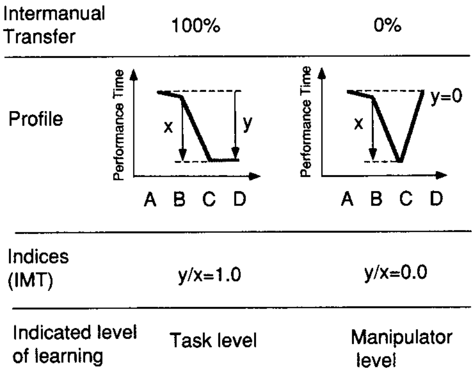

Figure 9. Predictions concerning intermanual transfer (IMT) in Experiment 3. A, B, C, and D in the middle of the figure correspond to pretest, beginning of training, end of training, and posttest, respectively.

Here, the denominator indicates the amount of learning measured within the hand and the numerator indicates the amount of learning measured between the pretest and the posttest with the untrained hand. If there is no intermanual transfer, the numerator is 0 and IMT = 0. If there is complete intermanual transfer, on the contrary, the numerator is equal to the denominator and the IMT = 1. Any intermediate degree of intermanual transfer is indicated by a value between these extremes. As stated earlier, if learning occurs at the task level, intermanual transfer should be nearly 100%, whereas if learning occurred at the manipulator level, the intermanual transfer should be nearly 0%.

Results

In Figure 10, the averages of the PTs in the four blocks (pretest, beginning of training, end of training, and posttest) are plotted for each participant. The data for the participants in Group A are shown at the top, whereas the data for the participants in Group B are shown at the bottom.

Let us first focus on the learning process itself. During the training session, the learning proceeded as in Experiment 2 (compare the averages of the PTs at the beginning of training and at the end of training in Figure 10). We cannot directly compare the learning curves in Experiment 3 with those in Experiment 2 using the same statistical methods because the criteria for learning differed between them. The training was terminated after 120 trials in Experiment 2, but was terminated after the participants reached the criterion that was described above in Experiment 3. However, the majority of participants in Group A (16 out of 18) and all of the participants in Group B showed significant improvements during the training session (Mann–Whitney *U* test, $U < 27, p < .05$; comparing the PTs of the first and the last 10 trials). Two participants in Group A (S.A. and M.Z.) showed little improvement due to the learning. We return later to these individual differences in learning.

We now examine intermanual transfer. Figure 10 shows that almost all of the individual Group A and Group B profiles are similar to the L-shaped profile in the left column of Figure 9. Viewing these profiles, it is to be expected that the IMT indices should be high; this was confirmed by the IMTs calculated for each participant.

The top half of Figure 11 shows the IMT values. The mean IMT for the participants of Group A was 1.57 and that for the participants of Group B was .91. Both values are close to or higher than 1, although there are considerable individual differences. Thus, intermanual transfer was quite pronounced in general, a finding consistent with the hypothesis that the functional locus of visual–motor learning is at the task level and not at the manipulator level.

There seems to be a considerable difference between the two groups and, in fact, the IMTs in Group A (left hand–right hand–left hand) were significantly higher than in Group B (right hand–left hand–right hand) (Mann–Whitney *U* test: $U = 17, p < .02$). However, the very high IMTs of some participants, especially in Group A, may have depended a lot on the mathematical definition of IMT; because the amount of learning measured within the hand (the denominator on the right side of Equation 1) was very small in some cases, the total IMT could have become too large because of a small amount of noise.

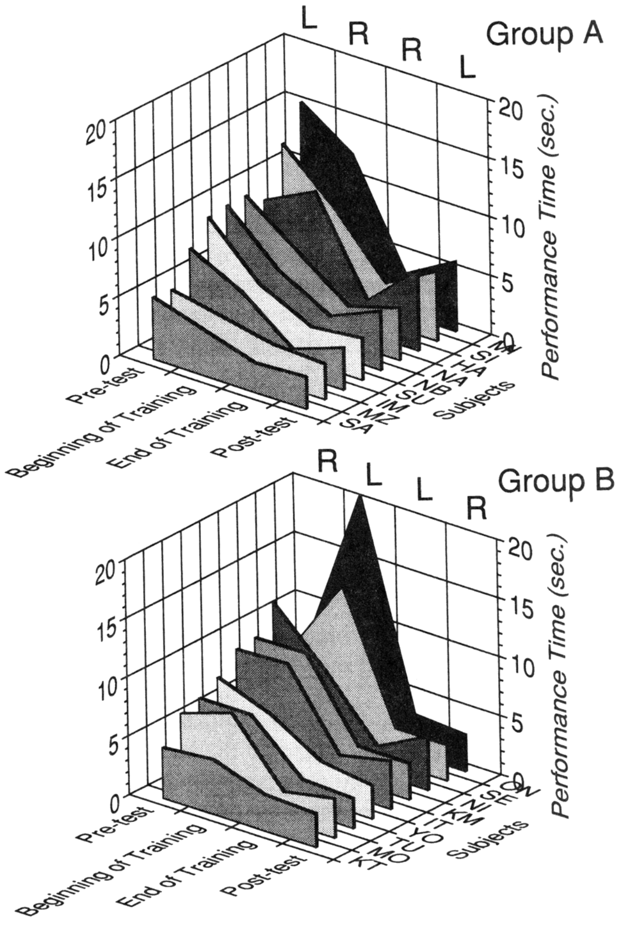

Figure 10. Average performance times for all participants. Each line corresponds to a participant; there were 9 participants in each group. L = left; R = right.

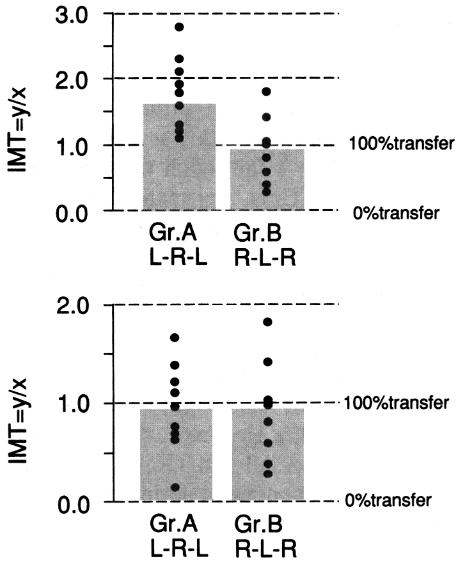

Figure 11. Intermanual transfers (IMTs) for each group are shown in the top half. Each dot indicates one participant's IMT and the hatched bar indicates the average IMT for the group. The bottom half shows the IMTs of Group A divided by 1.68 to cancel out the difference in the amount of learning between the groups. The IMTs of Group B were the same as those shown in the top half. L = left; R = right.

Discussion

We found considerable intermanual transfer between the hands, which we take as evidence for learning specific to the task level.[3] We also found that the transfer from the right hand to the left hand (Group A) is significantly greater than transfer from the left hand to the right hand (Group B). This tendency suggests that the degree of intermanual transfer from the preferred hand to the nonpreferred hand may be larger than that from the nonpreferred hand to the preferred hand. However, two other possibilities deserve closer examination: (a) the difference between the right and the left hand in terms of the amount of learning (savings in PT) and (b) extraordinary individuals in a group (the two participants, O.N. and S.E., who showed drastically different profiles from the other participants [see Figure 10] belonged to Group B).

As for savings in PT, from an examination of Figure 10 it appears that the left hand shows more pre- and postimprovement in terms of the PT than does the right hand. In other words, the amount of learning accomplished by the left hand is larger than that accomplished by the right. We measured the amount of learning by subtracting the mean PT of the last 10 trials from that of the first 10 trials. We obtained a mean value of 3.9 s (*SD* = 2.8) for Group A (training in the right hand) and 6.6 s (*SD* = 4.7) for Group B (training in the left hand). Thus, the ratio of learning in Group B to that in Group A is 1.68. Because this implies that the original value of the IMT denominator for Group A (learning in the right hand) was small compared with the numerator that reflected the left-hand performance, one might speculate that this led to the apparent asymmetry between the two groups as shown in the top half of Figure 11. We can eliminate this bias, however, by multiplying the denominator by 1.68 for Group A. The bottom half of Figure 11 shows the IMT values calculated using this procedure. The average of the IMT for the participants of Group A became 0.93 and nearly equal to that of Group B (0.91; Mann–Whitney U test, $U = 38.5$, $p > .1$), while our main finding of nearly 100% intermanual transfer remained.

Concerning the second point, the major cause of the difference between Groups A and B might be due to 2 participants in Group B (O.N. and S.E.) who did not originally show comparable performance between the right and left hands. We therefore excluded the data of O.N. and S.E. and recalculated the IMTs according to Equation 1. As a result, the mean IMT for the participants of Group B became 1.08, and there was no significant difference between the two groups (Mann–Whitney U test, $U = 15.5, p > .05$).[4]

We can sum up these results by saying that intermanual transfer was nearly 100% independent of the direction of transfer (i.e., transfer from the preferred hand to the nonpreferred hand and from the nonpreferred hand to the preferred hand) and that this finding is consistent with the hypothesis that the functional locus of visual–motor learning is at the task level, not the manipulator level.

General Discussion

Summary of Results

The goal of this research was to identify the locus of visual–motor learning. In Experiment 1, we confirmed Cunningham's (1989) earlier finding stating that rotations of 90° to 120° are the most difficult. Thus, we selected the 90° rotation for Experiment 2; we found that significant visual–motor learning occurs at 90° of rotation. In Experiment 3, we found nearly 100% intermanual transfer, regardless of the direction of transfer and concluded that the locus of visual–motor learning is at the task level. According to the schematic flowchart introduced in Figure 2, we conclude that learning occurs at a level that is not specific to either hand and where motor planning begins in the visual coordinates.

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[3] One would argue that nearly 100% intermanual transfer is a matter of course in the following case. Suppose that the movements made by two hands are mirror images of one another (about the midsagittal plane). Then what has been learned by one hand may seem to transfer perfectly to the other hand, even if the learning is entirely through manipulator level learning, owing to the mirror symmetry of the motor apparatus between the two hands. However, this would not really explain our results because we did not use a mirror-image task in the first place.

[4] If we first eliminate the two participants and then apply the same scaling procedure based on the amount of learning, then the new IMT for Group A would equal 1.37 and that for Group B would equal 1.08. Again, there is no significant difference between the two groups.

Other Possible Explanations for Nearly 100% Intermanual Transfer

However, other possible explanations for nearly 100% intermanual transfer must be considered. We ignored possibilities that the learning might occur at other levels (those not described in Figure 2). For example, when one acquires some complicated motor skills such as driving a car, an improvement in performance might be attributed to a higher conscious or cognitive level as opposed to an unconscious level including what we call the task level.[5]

Cunningham and Vardi (1990) reported that under rotational visual feedback, a participant can acquire the target quite easily with little training. In their experiment, participants tended to move in arcs and spirals. This strategy gave the participants a sense of control and allowed them to acquire the target relatively quickly and efficiently. Thus, the reason for different pretest and posttest performances in our study might be attributed to whether the participant acquired the "arc strategy" or not. If so, the reason for the large amount of IMT can be attributed to a change in strategy by the participants.

Figure 12 shows the trajectories of four participants who had the highest or lowest IMT in each group. As one can see, the character of the trajectories was different for each participant. In the last 10 trials of training and in the posttest, it is hard to find arcs and spirals except for participant O.N. However, the trajectories of S.U. and Y.O., who scored the highest IMT in Group A and Group B, were rather straight in the posttest. We further analyzed the data in the posttest for these participants using the same methods as did Cunningham and Vardi (1990) to confirm our visual inspection (see Appendix A). The results suggest that the large values of IMT cannot be attributed to an arc strategy.

As mentioned in the introduction, there are several factors that have been reported to affect the degree of intermanual transfer, in previous work on the intermanual transfer focusing on the prism's aftereffect. Among them, there are several possible explanations for the nearly 100% intermanual transfer, other than our hypothesis, including the training schedule of visual–motor learning and the availability of visual feedback. However, a careful examination of these factors indicated that our results could not be explained by them (for more details, see Appendix B). Therefore, we conclude that learning occurred at the task level.

A Common Framework for Computational, Physiological, and Behavioral Studies

Our introduction explained how the concepts of task level programming and manipulator level programming are useful in specifying the locus of visual–motor learning and in connecting intermanual transfer to the theoretical models proposed in the computational approach for human motor control. The concepts are also partly consistent with some physiological studies as described below.

There are two discernible questions about human visual–motor systems. The first question concerns the underlying neural circuit that implements motor performance. The second question, a more significant one, concerns the changes responsible for visual–motor learning, and we addressed the second issue in the current study by examining the intermanual transfer of acquired visual–motor skills. With regard to the first question, the computational distinction of the task and manipulator levels is at least partly consistent with physiological findings. Tanji, Okano, and Sato (1987) suggested that the firing rates of the primary motor cortex neurons are simply correlated with activities in the contralateral muscles. Conversely, the majority of nonprimary motor cortices such as the supplementary motor cortex and the premotor cortex do not code the activity of particular muscles because their discharge rates are independent of whether the right or the left hand is used (i.e., their firing rates increased when the monkey used the right hand as well as the left hand). Rather, they are related to the particular motor task (in this case pressing a button). These physiological findings, in line with the computational framework described in the introduction, indicate that there are two functional levels in motor control systems: one level is hand- or muscle-specific manipulator level programming and the other is nonspecific task level programming.

Unfortunately, there is not much evidence supporting the neurological locus or correlates of visual–motor learning. Motor learning is thought not to involve the motor cortex so much as the subcortical structure and the cerebellum (e.g., Ito, 1989). There is, however, no physiological evidence related to the task and manipulator levels in these structures. It would be intriguing to see whether there are also two distinguishable subcortical loci or neural populations corresponding to the task and manipulator levels, and whether synaptic changes underlying a particular kind of movement occur in a particular locus or population.

Even though intermanual transfer has been studied in psychology for many years, not much communication has occurred across computational, physiological, and behavioral studies, mostly because of the lack of a common theoretical framework and terminology. The investigation of intermanual transfer in relation to the theoretical distinction between task level and manipulator level, which have been accepted in computational and neurological approaches, however, exemplifies a potential paradigm for fruitful interaction.

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[5] Critical factors for intermanual transfer have been viewed as more central, such as a rule or strategy, whereas those leading to no intermanual transfer have been viewed as more peripheral (Welch, 1978). According to this distinction, both task and manipulator levels may belong to the peripheral level because neither of them belongs to a higher conscious or cognitive level (i.e., the rule or strategy). However, learning at the task level should lead to perfect intermanual transfer because it is shared commonly between the left hand's and the right hand's control systems.

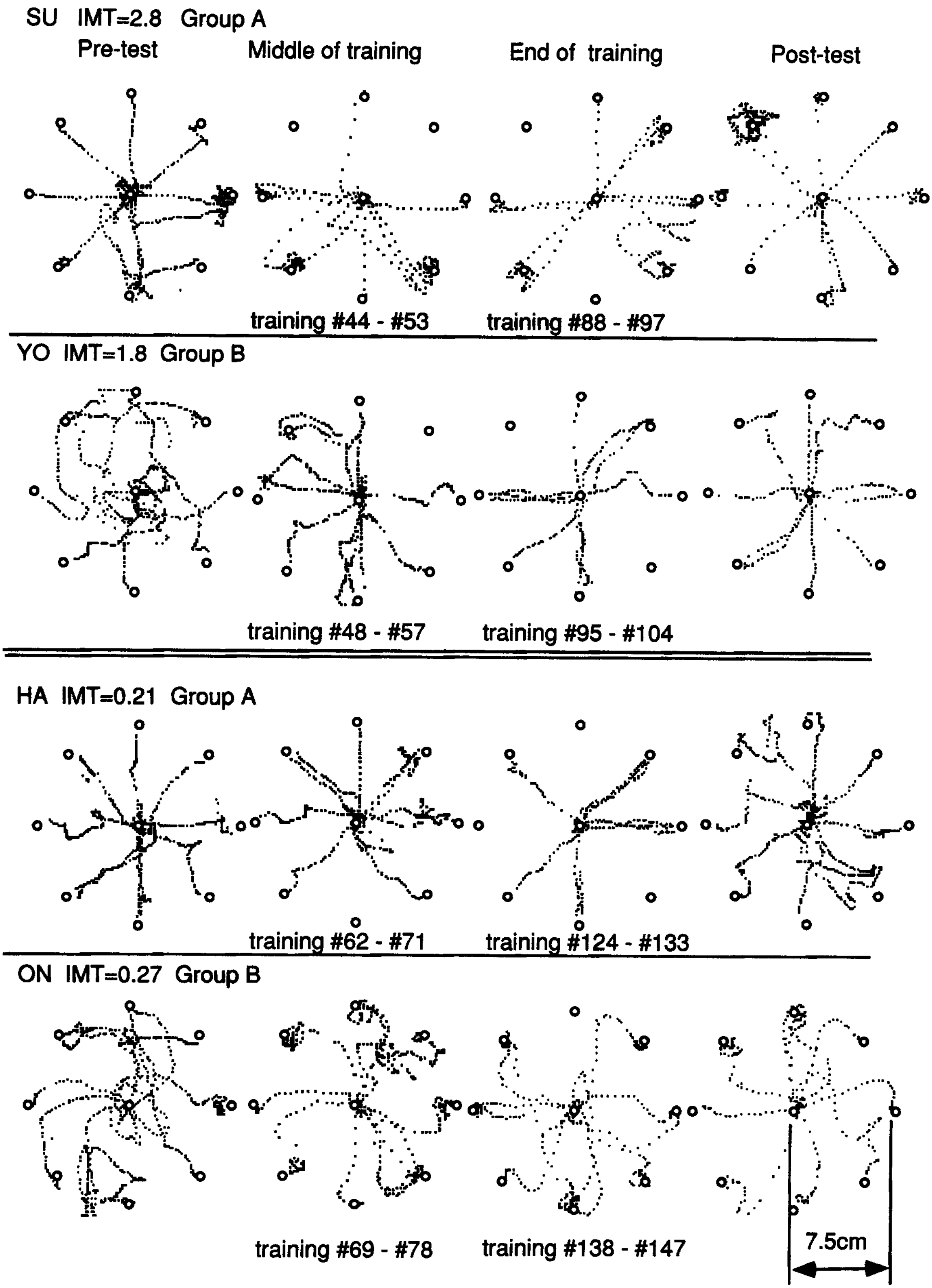

Figure 12. Trajectories of 4 participants who marked the highest or lowest intermanual transfer (IMT) in each group. S.U. and Y.O. scored the highest IMT in Group A and Group B, respectively. H.A. and O.N. scored the lowest IMT in Group A and Group B, respectively.

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Appendix A

Analysis of Trajectory Using the Methods of Cunningham and Vardi (1990)

We analyzed the data in the posttest for participants O.N., S.U., and Y.O. using the methods of Cunningham and Vardi (1990). An angle ϕ was obtained at each point in a movement path by determining the angle between the target direction and the tangent to the curve at that point (Figure A1, adopted from Cunningham & Vardi, 1990); ϕ was analyzed as a function of distance from the target, r. According to Cunningham and Vardi, if the participant adopts the arc strategy, the trajectories become spiral or semicircular. For spiral paths, ϕ should be constant and greater than 0 radian when plotted against r. For semicircular paths, ϕ should decrease monotonically. However, for straight paths, ϕ should be constant and near 0 radians.

In Figure A2, ϕ is plotted against r for each of the 4 participants who marked the highest or lowest IMT in each group for the first three trials. In the case of O.N., ϕ decreased monotonically near the target (No. 1) or was constantly greater than 0 (No. 2) as indicated with lines in Figure A2. This suggests that the participant partly adopted the arc strategy in the posttest. However, in the case of participants S.U. and Y.O., who scored the highest IMT in their respective group, ϕ was constant and 0 radian in most parts of the

(*Appendix A continues on next page*)

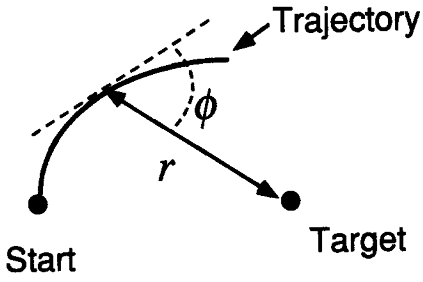

Figure A1. Microanalysis of trajectories. The angle ϕ at each point in the movement path was determined by measuring the angle between the target direction and the tangent to the curve at that point. The distance between the target and the start was labeled as r. From "A Vector-Sum Process Produces Curved Aiming Paths Under Rotated Visual–Motor Mappings," by H. Cunningham and I. Vardi, 1990, *Biological Cybernetics, 64,* p. 21. Copyright 1990 by Springer-Verlag. Adapted with permission.

profiles except the first trial. This suggests that movements were corrective or that the participants used an arc strategy immediately after the tested hand was changed, but not any time after that.

According to Cunningham (personal communication, 1993, see also Cunningham & Vardi, 1990), the "arc strategy" might be most evident in the middle of training because it takes participants some trials to find the strategy. In fact, in some trials in the middle stage of training, the trajectories tended to be semicircular. As examples, it seems that the arc strategy is more evident in the middle of training in all trajectories for O.N. and some for Y.O. (see Figure 12). Therefore, we cannot deny the possibility that the participants used the arc strategy to help them learn the task. However, not all participants who scored a high IMT used it at the last stage of training and in the posttest as shown in Figure 12 and Figure A2.

The apparent discrepancy between these results in the posttest and Cunningham and Vardi's (1990) results might stem from the different instructions to the participants and different stages of learning. In their experiment, as stated in the beginning of this

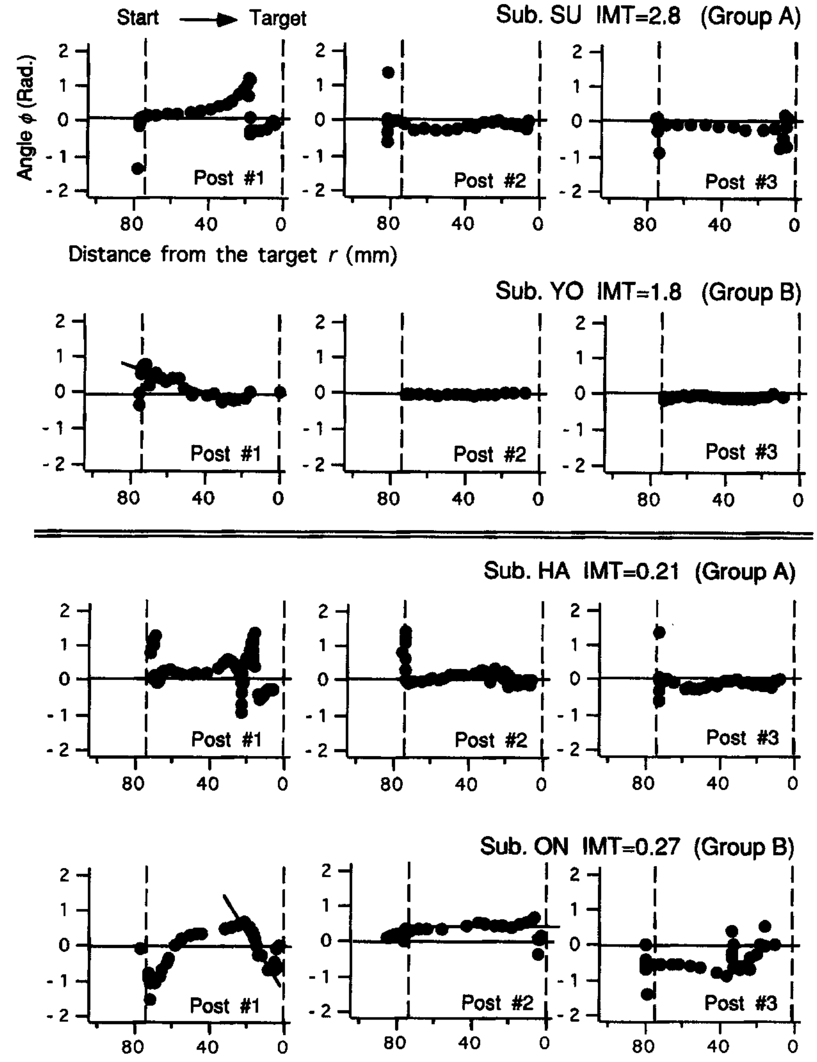

Figure A2. Functions relating angle ϕ to the distance from target r for participants (Sub.) S.U., Y.O., H.A., and O.N. The data are plotted separately for the first three trials in the posttest (post).

article, speed was not emphasized and the participants were not trained as much as in our experiments. It is well known that with learning and practice, movements tend to be performed more smoothly and gracefully (Georgopoulos, Kalaska, & Massey, 1981). Flash and Hogan (1985) formulated a mathematical model for smooth and unconstrained movements. They predicted a straight hand trajectory with a single-peak, bell-shaped velocity profile when movement is between pairs of targets. In accordance with this, the participants who scored high IMTs in our experiments did not adopt the arc strategy but moved their arms naturally so that the hand trajectory was almost straight even under the condition of rotated visual feedback after training. In fact, the participants in Experiment 2 arrived at a given target within 3 s after intensive training of 120 trials; the velocity profiles with a single peak (see Figure 8) indicate that their movements were highly ballistic. The PT of 3 s is nearly comparable to those of the untrained participants in Experiment 1 under the condition of 0° of rotation. It is obvious therefore that trained participants can get a target under any rotational transformation as rapidly as under normal condition (0° rotation). Thus, the reason for the large values of IMT cannot be attributed to a change in strategy by the participants.

Appendix B

Relevant Factors That Affect the Degree of Intermanual Transfer

Among the factors that have been reported to affect the degree of intermanual transfer in previous work focusing on the prism aftereffect, there are two potentially relevant factors that are specific to our experimental paradigm. We examined whether these factors could explain the nearly 100% intermanual transfer found in our study; however, they could not as described below.

Training Schedule of Visual–Motor Learning

The effect of massed and spaced training was suggested by Taub and Goldberg (1973). According to their results, intermanual transfer occurs more extensively under the condition of spaced training. In their experiment, however, intermanual transfer was only 59% under a spaced training condition, in which participants switched between training sessions and took breaks every 30 s. In our experiments, on the contrary, training continued with breaks of no more than 2 s or 3 s and thus, in their terminology, should be considered a massed training. Yet, nearly 100% intermanual transfer was observed. The unusually high degree of intermanual transfer obtained in our study thus could not be attributed to the type of training.

Availability of Visual Feedback

Cohen (1967) reported that intermanual transfer occurs under terminal visual feedback and does not occur under continuous feedback. In our experiments, however, visual feedback was continuously available to the participants; from Cohen's viewpoint, this is an unlikely condition for intermanual transfer to occur. Yet, nearly 100% intermanual transfer was observed.

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