N90-22947

DIRECTION OF MOVEMENT EFFECTS UNDER TRANSFORMED VISUAL/MOTOR MAPPINGS

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SUMMARY

Performance in a discrete aiming task was compared under several transformed visual/motor mappings: rotations by 45°, 90°, 135°, and 180° and reflections about the horizontal and the vertical midlines. Eight aiming targets were used, corresponding to eight directions of movement: up, down, right, left, up-right, down-left, up-left, and down-right. Direction of movement effects were characterized in terms of separable visual and motor direction components, and two kinds of direction of movement effects were considered. First, a direction of movement effect paralleling that seen in rapid aiming under the usual nontransformed mapping might be seen. If it is seen for motor directions, but not visual directions, then this supports a motor factor hypothesis for the effects seen under the nontransformed mapping. Second, because rotations, but not reflections, are physically realizable two-dimensional (2-D) transformations, a visual/motor control system which is sensitive to physical constraints should perform reflections, but not rotations, in a piecemeal fashion. Results supported the hypothesis that a motor factor having to do with complexity of limb movement accounts for differences in movement accuracy between right and left oblique directions. Direction of movement effects were more evident in reflections than in rotations, and were consistent with the hypothesis that the visual/motor-control system seeks a physically realizable 2-D rotation solution to reflections. Results also suggested that reversal of two orthogonal basis dimensions is far less difficult than reversing only one and leaving the other intact.

INTRODUCTION

This research investigates directional nonuniformities in the performance of a 2-D discrete aiming task, under transformed mappings between visual and motor spaces. Various rearrangements of the visual/motor map have been studied over the years (see Howard, 1982, for an excellent review). This work has focused primarily on the process of adaptation to visual/motor transformations. The present research, in contrast, compares the effects of different transformations and examines direction of movement effects within and between different transformations.

Direction of movement effects (DMEs) have important implications for our understanding of human visual/motor control. If there is nonuniformity in performance under physically uniform conditions, this reveals something about the organization of the internal representation of external space and about the mechanisms involved in visual/motor control. DMEs also are of practical importance because they can lead to biases in an operator's input to a system. Such biases are not easily detected when evaluating overall performance of the task, because they involve only a subset of the inputs. Understanding this source of bias would allow the development of systems that prevent biases or correct for them during operation.

In this research, visually guided aiming has been studied under two kinds of transformation of the usual directional mapping between a horizontal input surface (motor space) and a vertical display screen (visual space), which is such that:

Right –> Right
Left –> Left
Forward –> Up
Backward –> Down

This mapping is a natural one that humans as young as 3 yr of age can do immediately without any period of adaptation. This mapping will be referred to as the "usual" or "nontransformed" mapping.

The transformations that were studied constitute a subset of the linear orthogonal transformations. They were 1) rotations about the center of the space and 2) reflections about axes in the space. Rotations and reflections both preserve line length, angles, and parallelism of points in the original space when mapped into corresponding points in the image space. In general, the expression:

$$TX = X'$$

describes a transformation, T, of points $X = [x \;\; y]$ in the original space into points $X' = [x' \;\; y']$ in the image space. In this research, T took one of the following forms:

$$T_{ROT} = \begin{bmatrix} \cos(\theta) & -\sin(\theta) \\ \sin(\theta) & \cos(\theta) \end{bmatrix}$$

$$T_{HREF} = \begin{bmatrix} -1 & 0 \\ 0 & 1 \end{bmatrix}$$

$$T_{VREF} = \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}$$

$$T_{OBREF} = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}$$

These transformations represent, respectively, rotation about the center of the 2-D space by angle q, reflection about the horizontal midline of the space, reflection about the vertical midline, and reflection about a 45° line going through the center of the space.

METHODS

Six right-handed subjects performed a discrete aiming task with multiple possible target positions. The visual display was a vertical CRT screen and the motor input was movement of a hand-held stylus on a horizontal digitizing tablet. There were eight possible target positions, arranged at 45° intervals around the center. An aiming trial consisted of 1) the subject aligning the cursor with a marker at the center of the display screen; 2) a cueing tone sounding; 3) after a variable foreperiod (250 to 750 msec), a target appearing in one of the target positions; 4) the subject capturing the target by moving the cursor into alignment with it; and 5) the target extinguishing. Subjects were instructed to emphasize accuracy over speed and to execute as straight a trajectory as possible on every trial.

Each experimental session consisted of 32 baseline trials under the usual mapping, followed by 128 trials under one of the six transformed mappings: rotation of 45°, 90°, 135°, or 180°, or reflection about the vertical midline or about the horizontal midline. Transformations of the motor space relative to the visual space were effected using a combination of software manipulation and physical rotation of the digitizing tablet.

Root-mean-squared error (RMS ERROR) measured the deviation of a trajectory from a straight line and is reported here as the measure of difficulty experienced by subjects under the various visual/motor mappings. Reaction time and angular error of the initial segment of the trajectory were also obtained on each aiming trial, and are reported elsewhere (Cunningham, 1987a).

HYPOTHESES

Two aspects of DMEs were considered, and they correspond to two specific questions that were asked. First, can DMEs observed under transformed mappings help us to understand DMEs observed under nontransformed mappings? Previous work by this author (Cunningham, 1987b) has shown that under the nontransformed mapping, movement in some directions produces more error than movement in others. Specifically, among right-handed subjects movement along the left oblique produces more error than movement along the right oblique, and horizontal movement produces more error than vertical movement. Are these directional nonuniformities due to properties of the motor system or to nonmotor properties of visual or cognitive processes? Under the nontransformed visual/motor mapping, motor direction and nonmotor direction are congruent (i.e., confounded). Testing left-handed subjects will not disconfound them because it is possible that left-handers have reversed lateralization of information processing at many levels, not just in the motor system. Transformation of the visual/motor mapping, however, allows us to disconfound motor and nonmotor factors because directions of movement are no longer aligned in the usual way. Under a 90° rotation, for example, the visual right oblique becomes the motor left oblique, and vice versa. Under a 135° rotation, visual vertical corresponds to motor right oblique, and so forth. Thus it was asked: Will the expected pattern of DMEs be observed under transformed visual/motor mappings and, if so, will it be observed in display directions only (visual), in tablet directions only (motor), or in both?

The second question arises from considerations of the properties of the two kinds of transformations studied in this research: rotations and reflections. These are both linear orthogonal transformations, and so are mathematically similar. They differ, however, in one important respect: they are not equally physically realizable operations. A rotation of points on a 2-D surface is a rigid motion that can be realized in two dimensions. A reflection of points on a 2-D surface, however, is neither rigid nor physically realizable in two dimensions. Are the mechanisms responsible for visual/motor control sensitive to this difference? If so, performance under reflections should be qualitatively different from that under rotations. Specifically, it was asked: Is directional nonuniformity more likely to occur under reflection than under rotation as the system seeks a physically realizable solution to the transformation?

RESULTS

Transformation condition exerted an important influence on aiming error. On average, the four rotations differed both from one another and from the reflections. The condition which produced the highest average RMS ERROR was the 90° rotation. This was followed by the two reflections (which were the same) and the 135° rotation. The 45° and 180° rotations produced the least error and were similar to one another. These averages are for all movement directions under a particular transformation, and they are consistent with results obtained by other investigators in a three-dimensional tracking task under transformed visual/motor mappings (Kim et al., 1987). DMEs were also seen under both kinds of transformation, but they were qualitatively different under rotation and reflection. In figure 1, RMS ERROR under the four rotation conditions is plotted against axis of movement: horizontal (right and left), vertical (up and down), right oblique (up-right and down-left), and left oblique (up-left and down-right). Axes of movement correspond to directions of movement on the tablet (motor direction), irrespective of display direction. The vertical offset of the curves for each condition indicates the overall effect of the transformation condition. The expected right oblique/left oblique difference is seen for the 90° and 135° rotations. This is also true for the 45° condition, although the scale of this plot makes the difference less obvious. The horizontal-vertical difference seen under nontransformed mapping was *not* preserved in either visual or motor coordinate systems under rotation.

An interesting and very different pattern of DMEs emerges under the reflection conditions. Figure 2 shows RMS ERROR under a reflection about the horizontal midline. Note that under this transformation, the horizontal axis (axis of reflection) is preserved: direction of travel along the axis is the same as under the nontransformed mapping. The vertical axis is reversed. The right and left obliques are exchanged, which is equivalent to rotating each of them by 90°. The surprising result shown in this figure is that the axis along which sign is preserved (right and left) has considerably higher aiming error than that along which sign is reversed (up and down). The axes corresponding to 90° rotations also exhibit high error.

Figure 3 demonstrates that this effect is also seen under the reflection about the vertical axis. Here, vertical axis movement is preserved as in the nontransformed mapping, and the error for movements along that axis is high. The horizontal axis is reversed, and error for movements along that axis is low. Again, error for movements along the other two axes is also high. The significance of direction of movement under reflections appears to relate not to the orientation of a movement axis in external space, but rather to its orientation with respect to the transformation performed on the space.

PRELIMINARY DISCUSSION

DMEs were observed under both rotation and reflection transformations. Under rotation, the pattern of results for right versus left oblique confirmed a probable motor locus for the right oblique advantage. This was seen in three out of the four rotation transformations and was especially strong in those where the overall error is high (90° and 135° rotations). This motor effect is consistent with the fact that movement along the right oblique can be done with arm movements from the elbow, whereas movement along the left oblique requires movement from the shoulder. Movement from the shoulder involves more joints and the control of more mass than does movement from the elbow.

The DMEs seen under reflection are qualitatively different from those seen under rotation. They are also large. Under reflection, the reversed axis has the lowest aiming error, and the two oblique axes have the highest. The error along the axis of reflection was surprisingly high, considering that the reflection transformation preserves that axis entirely. To what may we attribute these directional nonuniformities seen under reflection? There are two separate questions to answer:

1. Why do the oblique axes exhibit higher error than the nonoblique axes? Is it because they are oblique or because they are transformed by the equivalent of a 90° rotation?

2. Why do the preserved axes exhibit greater error than the reversed axes?

Another Transformation: Oblique Reflection

In order to answer the first question, an additional condition was run: reflection about an oblique axis. Under this reflection, the right oblique was the axis of reflection and so was preserved. The left oblique was thus reversed. The horizontal and vertical axes were exchanged for one another, which is equivalent to a 90° rotation of each of them. Figure 4 shows the result of this reflection. Observed DMEs are consistent with those found under horizontal- and vertical-axis reflection. The reversed axis exhibits low error and the preserved axis exhibits high error. The axes whose transformation is equivalent to a 90° rotation also exhibit high error.

GENERAL DISCUSSION

DMEs were observed under several different transformations of the usual mapping between visual (display) space and motor (input) space. Two types of DMEs were seen. First, aiming error was lower for right oblique motor directions than for left oblique motor directions, irrespective of visual direction. This supports the hypothesis that the right oblique "advantage" seen under nontransformed visual/motor mapping is due to motor factors. A tendency for vertical error to be lower than horizontal error under the nontransformed mapping was *not* seen in either the motor or the visual directions under the transformed mappings.

DMEs also differed qualitatively between rotations, on the one hand, and reflections, on the other. Under reflection, DMEs are related to an axis of movement's orientation with respect to the axis of reflection, not with respect to external space. The fact that human performance exhibits this particular kind of directional nonuniformity under reflection, but not under rotation, is consistent with the hypothesis that the human representation of 2-D space is constrained by physical realizability. The pattern of DMEs under reflection suggests that the human imposes a 2-D rotation solution on the reflection condition. Axes whose transformation is equivalent to a 180° rotation exhibit less error than those whose transformation is equivalent to a 90° rotation, just as a 180° rotation of the entire space produces less error, in all directions, than a 90° rotation of the entire space.

Another interesting aspect of the DMEs found under reflection (and one which complicates somewhat the 2-D solution hypothesis) is the strong tendency for the reversed axes to exhibit lower error than the nonreversed axes. This was seen in every reflection. This is probably due to error correction during movement execution. During execution of a movement, subtle corrections are required to keep the trajectory on a straight path toward the target. For a straight-line trajectory, corrective movements will have a large vector component in the dimension orthogonal to the straight-line path. Under reflection, when moving along the axis of reflection (the preserved axis), the orthogonal dimension is reversed. The small, quick, and largely automatic corrections made during movement execution will initially be in the wrong direction. As the error is detected, further automatic attempts to correct it may result in enhancing it instead. This is equivalent to reversing the sign of a feedback loop and the result is similar: error "blows up." In the case of movement along the reversed dimension, the orthogonal dimension (dimension of correction) is preserved and so automatic corrections reduce the error as they should.

In summary, DMEs are intrinsic to discrete aiming on a 2-D surface. The mechanisms responsible for visual/motor control are sensitive to motor factors having to do with the number of joints involved in movement in a given direction. They also appear to be constrained to find 2-D physically realizable solutions to visual/motor transformations, even when these solutions do not exist.

REFERENCES

Cunningham, H. A. (1987a). Development of visual-motor control. Submitted for publication to J. Exp. Psychol: Human Percept. Perf.

Cunningham, H. A. (1987b). Human motor control under transformed visual-motor mappings. Submitted for publication to Biol. Cybernet.

Howard, Ian P. (1982) Human Visual Orientation. Toronto: John Wiley & Sons.

Kim, W. S., Ellis, S. R., Tyler, M. E., Hannaford, B., and Stark, L. W. (1987) Quantitative evaluation of perspective and stereoscopic displays in three-axis manual tracking tasks. IEEE Trans. Syst., Man, and Cybernetics, 17, 61-72.

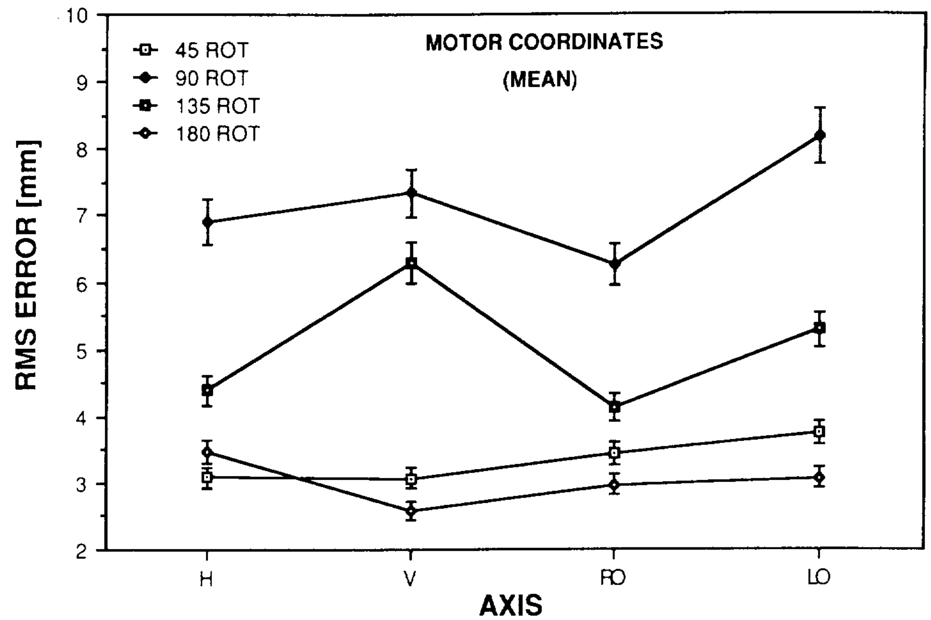

Figure 1.– RMS ERROR plotted against axis of movement in motor coordinates (directions of movement on the tablet, irrespective of display direction). Axes are horizontal, vertical, right oblique, and left oblique. Note that the right oblique/left oblique difference seen under the usual mapping is preserved in motor coordinates and so is probably motor in origin. The horizontal/vertical difference observed under the usual mapping is *not* preserved.

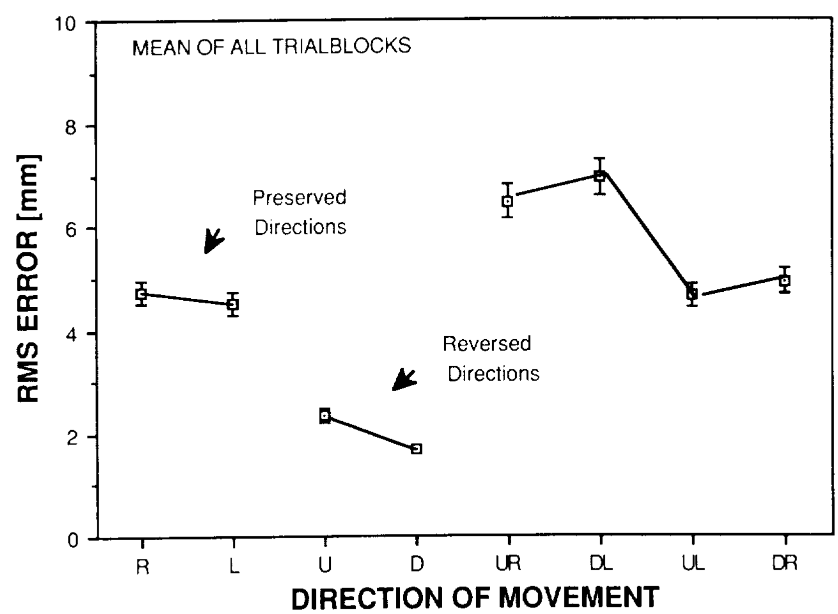

Figure 2.– RMS ERROR plotted against direction of movement for eight directions. The horizontal axis (right and left) is preserved and the vertical axis (up and down) is reversed. Oblique axes correspond to a 90° rotation. Note that the oblique axes have the highest error, the reversed axis the least, the preserved axis intermediate. Note also that the "motor oblique effect" is present (right and left obliques are exchanged).

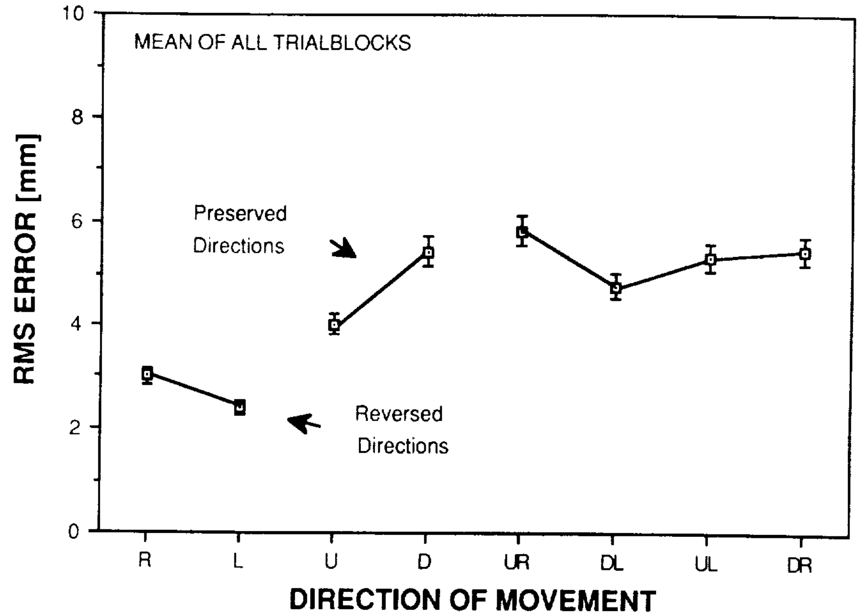

Figure 3.– RMS ERROR plotted against direction of movement under reflection about the vertical axis. The pattern of errors with respect to the oblique axes, the preserved axis, and the reversed axis is essentially the same as that seen under horizontal reflection.

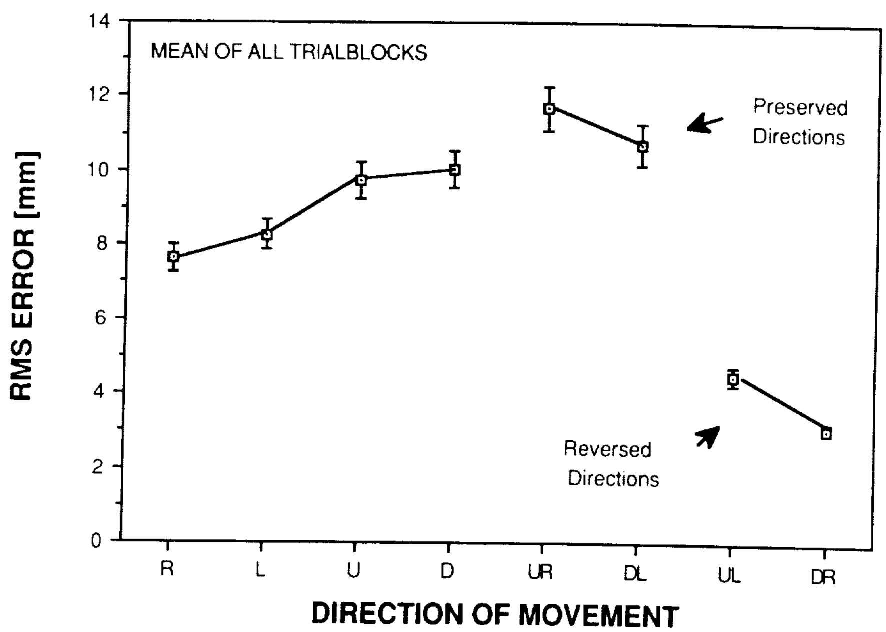

Figure 4.– Under reflection about the right oblique axis, the reversed and preserved axes are the obliques. Yet the same pattern of error is seen: reversed axis exhibits low error, and preserved axis and 90° rotation axes exhibit high error.