On the Use of Different Spatial Reference Frames for Movement Control

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Previous work has shown that amplitude and direction are two independently controlled parameters of aimed arm movements, and performance, therefore, suffers when they must be decomposed into Cartesian coordinates. We now compare decomposition into different coordinate systems. Subjects pointed at visual targets in 2-D with a cursor, using a two-axis joystick or two single-axis joysticks. In the latter case, joystick axes were aligned with the subjects’ body axes, were rotated by $-45^\circ$, or were oblique (i.e., one axis was in an egocentric frame and the other was rotated by $-45^\circ$). Cursor direction always corresponded to joystick direction. We found that compared with the two-axis joystick, responses with single-axis joysticks were slower and less accurate when the axes were oriented egocentrically; the deficit was even more pronounced when the axes were rotated and was most pronounced when they were oblique. This confirms that decomposition of motor commands is computationally demanding and documents that this demand is lowest for egocentric, higher for rotated, and highest for oblique coordinates. We conclude that most current vehicles use computationally demanding man–machine interfaces.

Keywords: motor control, coordinate systems, decomposition, spatial orientation

Several previous studies have compared the manual tracking performance of human subjects under two conditions: when the $x$ and $y$ components of cursor movement were controlled by a dual-axis joystick operated with one hand and when they were controlled by two single-axis joysticks operated with both hands. In either case, joystick and cursor motion was congruent in that left–right joystick displacement led to a left–right cursor movement and up–down joystick displacement to an up–down cursor movement. All authors reported that tracking performance in the unimanual condition was superior to that in the bimanual condition (Bartram, Banerji, Rothwell, & Smith, 1985; Chernikoff & LeMay, 1963; Fracker & Wickens, 1989; Regan, 1960). When interpreting this pattern of findings, it should be noted that the experimental conditions differed in two respects: the bimanual condition required a coordination of muscles from different limbs, and...
it also called for a decomposition of the motor command into two orthogonal components.

Either or both facts might account for the findings just mentioned, but experimental evidence favors the latter over the former interpretation. For instance, one group of studies evaluated the “motor equivalence principle” (Lashley, 1942) and reported that end-effector kinematics are preserved when a given movement is executed with different force levels, muscle groups, or limbs (Flanagan & Tresilian, 1994; Grasso, Bianchi, & Lacquaniti, 1998; Levin, Wenderoth, Steyvers, & Swinnen, 2003; Rijnjtes et al., 1999; Wing, 2000) and when it is executed with different combinations of body segments (Marteniuk, Ivens, & Bertram, 2000; Smeets & Brenner, 2001). These findings argue against the view that two limbs are more difficult to control than a single limb. A second group of studies investigated which variables are controlled by the motor system and found that amplitude and direction are two independently controlled movement parameters (Bock & Arnold, 1992, 1993; de Graaf, van der Gon, & Sittig, 1996; Favilla, Hening, & Ghez, 1989; Flanders & Cordo, 1989; Georgopoulos, Kalaska, Crutcher, Caminiti, & Massey, 1984; Gordon, Ghiardi, & Ghez, 1994), whereas the two Cartesian components of a movement are not independently controlled (Bock, 1992; Engel & Soechting, 2000). These findings suggest that the natural reference frame for motor control is polar rather than Cartesian. Thus, both groups of studies favor the interpretation that bimanual performance is reduced because the motor command must be decomposed into two Cartesian components and not because it must be distributed across two limbs.

The purpose of the current study was to further explore the difference between manual performance with a two-axis joystick versus two single-axis joysticks. We used pointing rather than tracking movements to determine whether the difference in joysticks reflects general principles of motor control. We further used differently oriented joystick axes to find out whether transformation of the motor command from a polar into another reference frame is more difficult with some reference frames than with others.

Methods

Thirty-two adults age 18–35 years (16 men, 16 women) participated in the experiment. They were right-handed (Edinburgh Crovitz Inventory Score > 75), exhibited no overt sensorimotor deficits, and had no prior experience in similar research. All subjects signed an informed consent statement, and experimental procedures were approved by the Human Research Ethics Committee of the Queensland University of Technology.

The experimental setup is illustrated in Figure 1. Subjects sat in a dimly lit room looking at a computer monitor located in their frontal plane at eye level. The monitor was covered with a black mask, which obscured all but a circular aperture 40 cm in diameter, thus reducing visual references about the vertical and horizontal. Subjects grasped with their thumb and index finger one or two low-friction joysticks located 35 cm apart on a table in front of them. An occluding panel (not shown in Figure 1) prevented them from seeing their hands. The joysticks were not centered by springs; they were either free to move in two dimensions or were
physically constrained to move in one dimension only. The $x$ and $y$ position of both joysticks was registered through linear conductive plastic potentiometers, sampled by the computer with a resolution of 0.04° and 100 Hz, and displayed in real time as a cursor on the monitor. Cursor movement was the vector sum of the movements of both joysticks.

The subjects’ task was to point with the cursor quickly and accurately from the center of the monitor toward peripheral targets and back again. Each trial began with a central dot 1 cm in diameter. Subjects moved the cursor toward that dot, at which time it changed color. After 300 ms, the central dot was replaced by a target dot of 1 cm diameter. The target appeared in one of eight possible directions (22.5° to 337.5° in 45° increments, where 0° is to the right) and one of two possible distances (30 and 60 mm) from the center. It remained visible until 150 ms after movement onset or until the cursor reached the target, whichever came first. The central dot then reappeared, and the next trial commenced. To minimize anticipations and inadvertent movements about the center, a warning sounded
(“too fast”) if a movement started within 160 ms after target appearance, and the trial was reinitiated.

Testing was divided into blocks of 16 trials in which each of the 16 possible targets were presented once, in mixed order. Subjects were advised that they could pause after any block, to minimize fatigue. The experiment began with a baseline phase in which subjects completed two blocks using the right, unconstrained joystick with their right hand and two blocks using the left, unconstrained joystick with their left hand; the order of joysticks was counterbalanced across subjects. For the subsequent experimental phase, subjects were subdivided into four groups of eight. As shown in Figure 1, group CTR grasped an unconstrained joystick with both hands. Group EGO grasped a joystick constrained to fore-aft movement with one hand and a joystick constrained to left-right movement with the other hand. In group ROT, joystick axes were rotated by $-45^\circ$ with respect to group EGO; one hand and joystick moved the cursor from lower left to upper right and the other from upper left to lower right. In Group OBL, one hand and joystick were constrained to move fore-aft and the other to move $-45^\circ$ with respect to left-right. The assignment of hands to joysticks was counterbalanced within the subjects of each group. For example, four subjects from group EGO moved the right joystick with their right hand fore-aft and the left joystick with their left hand left-right; the other four subjects moved the right joystick with their right hand left-right and the left joystick with their left hand fore-aft. Subjects never had to cross their hands.

We calculated the following variables from the registered data of each trial:

- Reaction time (ms): interval between target appearance and response onset defined by a cursor displacement threshold of 1.96 mm.
- Angular error ($^\circ$): difference between response and target direction 100 ms after response onset (i.e., before error-correcting feedback could become effective). Positive values represent counterclockwise errors.
- Relative distance: response distance 100 ms after response onset, divided by target distance.

For further analyses, we determined the following performance measures for each block:

- Number of “misdirected responses” (i.e., abs[angular error] > 75$^\circ$). Misdirected responses were not included when calculating other performance measures.
- Mean reaction time (ms).
- Mean angular error ($^\circ$), with positive values indicating a consistent counterclockwise deviation of response directions.
- Number of responses along a single joystick axis (i.e., one of the joysticks remains below the displacement threshold); an increase of this measure above the values of group CTR would reflect a tendency to respond with one hand and joystick only.
• Standard deviation (°) of responses about their target-specific mean, that is

\[ sd = \sqrt{\frac{\sum_i \sum_t (r_{it} - R_t)^2}{(n-1)}} \]

where \( r_{it} \) is the error of the \( i \)th response to target direction \( t \), and \( R_t \) is the mean error of responses to target direction \( t \).

• Mean relative distance.

Performance measures from the baseline phase were submitted to analyses of variance (ANOVAs) with the between-factor group and the within-factor block. Performance measures from the experimental phase were adjusted by subtracting the pertinent baseline values, and the resultant above-baseline scores were submitted to ANOVAs with the same factorial structure. Significant effects of group were scrutinized by comparing the scores of either group with CTR using Tukey’s HSD tests.

Results

Figure 2 depicts the time course of all performance measures throughout the experiment separately for each group. All scores were relatively stable during the baseline phase, increased abruptly at the onset of the adaptation phase for most performance measures and groups, and then gradually returned toward baseline values. The increase was most pronounced in group OBL, followed by ROT, and then by EGO; little increase was observable for group CTR. The time course of return differed substantially between performance measures: relative distance normalized within 2 blocks, whereas standard deviation did not fully recover over the 16 blocks of the adaptation phase.

An ANOVA of baseline data (left part of Table 1) yielded significant effects of group for the performance measure standard deviation (group CTR varied more) and significant effects of block for the measures reaction time (gradual decrease), single-axis responses (increase in block 4), and relative distance (gradual increase). An ANOVA of above-baseline data from the adaptation phase (right part of Table 1) yielded significant effects of group for misdirected responses (post hoc: OBL > CTR, \( p < .05 \)), reaction time (post hoc: OBL > CTR & ROT > CTR, both \( p < .05 \)), angular error (not confirmed by post hoc tests, all \( p > .05 \)), single-axis responses (post hoc: OBL > CTR & OBL > ROT, both \( p < .001 \), and EGO > CTR & EGO > ROT, both \( p < .05 \)), and standard deviation (post hoc: OBL > CTR & ROT > CTR & EGO > CTR, all \( p < .01 \)). ANOVA further yielded significant effects of block on four measures and of Group × Block on two measures, thus reflecting the gradual normalization of performance observed in Figure 2.
Figure 2 — Time course of six performance measures in our four subject groups. Data points are the means across subjects for a given block, and error bars are the corresponding standard deviations. Note that performance deteriorates at the onset of the experimental phase (end of shaded area), particularly in group OBL.
Figure 2 (continued)
<table>
<thead>
<tr>
<th>Performance measure</th>
<th>Baseline</th>
<th>Above baseline</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Group (3, 28)</td>
<td>Block (3, 84)</td>
</tr>
<tr>
<td>Number misdirected</td>
<td>1.54</td>
<td>0.37</td>
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<tr>
<td>Reaction time</td>
<td>0.15</td>
<td>5.83&lt;sup&gt;b&lt;/sup&gt;</td>
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<tr>
<td>Angular error</td>
<td>1.32</td>
<td>1.85</td>
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<td>Number along joystick axis</td>
<td>0.15</td>
<td>2.91&lt;sup&gt;a&lt;/sup&gt;</td>
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<tr>
<td>Standard deviation</td>
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<td>2.51</td>
</tr>
<tr>
<td>Relative distance</td>
<td>0.18</td>
<td>4.60&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
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Note. Cell entries are F values.

<sup>a</sup> p < .05.

<sup>b</sup> p < .01.

<sup>c</sup> p < .001.
Discussion

We compared the execution of two-dimensional aiming movements in subjects using two single-axis joysticks, one in each hand, and in those using a two-axis joystick in one hand (baseline phase) or in both hands (experimental phase of group CTR). Our data document that manual performance was inferior with two joysticks: the number of misdirected responses was higher, and the remaining responses were characterized by an increased reaction time, an increased incidence of responses with one joystick and hand, an increased variability, and a reduced distance reached within the first 100 ms (i.e., a reduced initial velocity). These findings confirm previous reports that manual performance is degraded when two joysticks are used (Bartram et al., 1985; Chernikoff & LeMay, 1963; Fracker & Wickens, 1989; Regan, 1960) and extend them from tracking to pointing movements. By using six distinct performance measures rather than a single, global tracking score, our findings further show that the degradation is related to temporal (reaction time, relative distance) as well as spatial aspects of movement (misdirections, single-axis responses, standard deviation) and suggest that both movement preparation and execution processes are affected. Our data also show that the performance decrement is gradually compensated with practice; some spatial and temporal aspects of movement largely recovered within 16 trial blocks (i.e., misdirections, single-axis responses, relative distance), whereas others apparently required substantially more practice (reaction time, standard deviation).

Our findings suggest that the performance decrement is mildest when the axes of both joysticks are oriented parallel to an egocentric reference frame, higher when the two axes are rotated with respect to the egocentric frame but remain orthogonal, and highest when the two axes are oblique. These findings provide indirect support for the view (see the opening paragraphs of this article) that the main difficulty of two-joystick control is in subdividing the motor command into two components and not in distributing it across two limbs; performance decreased from EGO to ROT to OBL even though all three conditions equally necessitated the use of two limbs.

Findings reviewed in the opening paragraphs suggest that it is computationally demanding to transform a motor command from polar into Cartesian egocentric coordinates. The current pattern of findings indicates that it is even more demanding to transform it into rotated but orthogonal coordinates and still more demanding to transform it into oblique coordinates. The higher computational demand is reflected by the fact that movements take longer to prepare (reaction time), are slower (relative distance), less accurate (standard deviation, single-axis responses), and more error prone (misdirections).

It should be noted that, even though a rotation of the motor reference frame is computationally demanding, it still is much easier to achieve than a sensorimotor adaptation to rotated visual feedback. Responses during adaptation are also slower, more variable, and more error prone, but in addition, the mean angular error increases dramatically at the onset of the rotation and only returns to baseline values after about 100 trials (Pipereit, Bock, & Vercher, 2006; Seidler, 2006). In contrast, the mean angular error exhibited only subtle changes in the current study.
This difference between adaptation studies and the present work suggests that sensorimotor adaptation is based on a different principle than a rotation of the motor reference frame.

The outcome of the current study has obvious implications for human-operator scenarios. When controlling multidimensional object paths, operators should use a single multidimensional input device or, if this is not technically feasible, several low-dimensional devices oriented in an egocentric reference frame. We expect that this approach increases operator speed and accuracy and decreases operator errors. As straightforward as these recommendations might seem, they are typically violated by many man–machine interfaces, such as those used in a crane or backhoe. The violation is particularly dramatic in the most common everyday-life example of a human-operator scenario, namely, in car driving. The two-dimensional trajectory of a car is controlled by operating a wheel and two pedals (or a wheel, a lever, and three pedals), none of which correspond to the driver’s egocentric reference frame. However, joystick-operated vehicles are used with success by disabled drivers and in some forestry and construction operations. They also are under active investigation for other motor vehicles (Andonian, Rauch, & Bhise, 2003; Kelber et al., 2004).

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References


