

Individual differences in the programming of rapid bimanual movements: Are two modes better than one?

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ABSTRACT

International Journal of Exercise Science 9(3): 347-358, 2016. One of the challenges in performing simultaneous bimanual movements is to prevent interference from one limb to the other, thereby maintaining spatial accuracy in both limbs. Prior research has shown that when a longer distance movement is performed with a shorter movement, the shorter movement overshoots its target and the longer movement undershoots its target relative to control conditions where two shorter or two longer movements are made. The current experiment investigated the motor control strategies used by participants when performing simultaneous aiming movements combining both different and same distances. Participants ($N = 20$) made rapid lever-positioning movements (goal time to reversal was 350 ms) in the sagittal plane to 2 different spatial targets (20° and 60°) or the same targets (either 20° or 60°). Feedback about spatial accuracy was provided immediately after each trial. Constant error (CE) was measured for each distance based on 20 practice trials per condition. The CE from the same- and different-distance conditions were compared with separate one-way ANOVAs with repeated measures. Overshooting was shown of the 20° target and undershooting of the 60° target when the two distances were performed together. However, the movement amplitudes were positively correlated over trials in both the same- and different-distance conditions. A trial-by-trial analysis of the CE scores revealed both compensatory and non-compensatory strategies. The results suggest individual differences in how amplitude parameters are chosen for use with the generalized motor program in the control of bimanual aiming movements.

KEY WORDS: Individual differences, aiming accuracy, generalized motor programs.

INTRODUCTION

One of the challenges of bimanual motor learning is to make accurate movements without being influenced by movements of the other hand. For example, pianists and guitarists must learn to make accurate finger placements free from interference from the other hand performing movements different

in spatial and temporal characteristics. On the other hand, learning putting in golf may be enhanced because both hands perform the same action at the same time, which should reduce the interference between the hands. In any case, learners must acquire the capability of making individually accurate movements regardless of the context.

One of the most persistent results shown in studies of bimanual aiming movements has been the presence of assimilation effects, whereby the shorter distance target is overshoot and a longer distance target is undershot when different distance movements are performed simultaneously. The spatial errors generated by changing movement distances in this fashion have been termed spatial assimilation effects because movement amplitudes become more similar to one another compared to when the movements are made separately. The magnitude of spatial assimilation effects in aiming movements depend on a number of factors including the number of practice trials (14), handedness (16), movement time (18), the difference in the goal amplitudes (15), the amount of temporal overlap between movements (19, 27), the practice structure (7, 17, 20, 21), the availability and type of visual feedback (12, 22, 23) the number of movements in the sequence (30, 31), and the focus of attention (25).

According to theories of bimanual control, the hands are controlled by both common and hand-specific parameters (9, 11). Common parameters are those characteristics applied to both hands during simultaneous movement and include the order of events, relative timing, and relative force. Specific force and/or absolute time parameters can be applied to each hand in order to achieve a different spatial or temporal outcome in each hand, if needed. If the same movement distance, for example, is needed in each hand the same level of force can be applied via a common force parameter. If different distances are needed, then different force levels could be applied to each hand. However, the limitation of this programming model is that assimilation

effects were not addressed. A more recent theory by Marteniuk and colleagues (4, 5) builds on the earlier programming theories, but explains assimilation effects by proposing neural crosstalk between the specific parameters assigned to each hand. According to this theory, the distance or amplitude achieved by a given limb is done by setting a specific movement endpoint, and the speed of the limb is controlled by the intensity of the impulse applied to the limb. When the same distance is required in both hands, there is little effect of crosstalk between the left and right side of the nervous system since the same parameters are applied to both limbs. However, if different distances are required in each limb, then the parameters destined for each limb must necessarily be different. Due to the interconnection between the left and right sides of the nervous system at the subcortical level, the resulting output at the spinal level is an interaction between what was individually programmed for each limb. For example, suppose a 10 cm movement is required in the left limb and a 30 cm movement is required in the right limb. The resulting movement in the left limb will overshoot the target because the 30 cm parameter destined for the right limb interacts with the 10 cm command planned for the left limb. By the same token, the right limb would undershoot because the 30 cm command is minimized by the 10 cm command. The crosstalk theory behind bimanual control can explain why and how assimilation effects occur, but the theory has not addressed the issue of individual differences in bimanual control.

The evidence for assimilation effects in aiming movements is clearly strong and the data based on group means suggests that all

participants are affected by the interference in the programming process. However, due to the reliance on group means in many of the past studies, individual differences in the programming process have not been frequently studied. Nevertheless, a few studies have demonstrated individual differences in assimilation effects including the classic studies by Goodman, Kobayashi, and Kelso (2) and Kelso, Putman, and Goodman (3). In these studies participants made bimanual aiming movements to targets, with a hurdle placed in the path of only one hand. Some participants showed the same kinematic pattern in both hands even though one hand did not have to clear the hurdle, suggesting a strong spatial assimilation effect. Alternatively, some participants moved the hand on the non-hurdle side to the target with a different trajectory than the hand going over the hurdle, suggesting the movements did not interfere with one another. Thus, it is clearly possible for different participants to show different levels of interference, or use different strategies to perform the task over trials, but these findings have rarely been described in the literature on the accuracy of aiming movements. Therefore the goal of the present study was to describe the individual differences used by participants during practice of bimanual aiming movements involving the same-or different-distance goals.

METHODS

Participants

The participants were 20 undergraduate students (aged 18-28, male, $n = 10$, female, $n = 10$) at the University of Colorado. Based on the Edinburgh Handedness Inventory (6), the participants were right-handed with

laterality quotients (LQ) ranging from +28 to +100. All participants received course credit equal to 1% of their final course grade for their participation. The Human Research Committee at the University of Colorado approved the work and the participants signed an informed consent form before participating.

The apparatus (shown in Figure 1) was a Plexiglas platform on a standard table top, which was slotted to allow two aluminum hand levers (16 cm in length and 36.5 cm apart) to move only 75° in the sagittal plane, with the most proximal position called 0°. Precision potentiometers (Beckman Industrial, #3381, 10K) were affixed to the base of each lever so displacement could be recorded. The measurement error of the potentiometers was .1°. Due to the arrangement of the hand levers and the potentiometers, the hand and levers moved in a slightly curvilinear path such that the maximum vertical change in displacement was 3 cm. The maximum distance the levers could travel in the sagittal plane was approximately 22.5 cm. The output of the potentiometers were digitized on-line at 1000 Hz and stored on a PC. During testing, the apparatus and the participant's arms were covered with a cloth sheet (see Figure 2).

The goal for the participants was to make two quick lever-reversal movements to pre-assigned targets in two conditions. In the same-distance condition the goal was to reverse both levers at the same target distance, either 20° or 60°. These conditions are referred to as the 20°-20° and 60°-60° conditions, respectively. In the different-distance conditions, the goal was to reverse the left lever at the 20° target and reverse the



Figure 1. The lever apparatus used in the experiment.



Figure 2. A participant in the testing position. The apparatus is covered by a wooden frame and sheet.

right lever at the 60° target, or vice versa. These conditions are referred to as the 20°-60° and 60°-20° conditions, respectively. The participants were instructed to make smooth movements out to the reversal point and back to the 0° starting position, without waiting or hesitating at the reversal point. See Figure 3 for sample potentiometer outputs for one trial in the 60°-20° condition. The goal movement time (MT) was 700 ms for each movement and was defined as the time to move the lever from the start position to the reversal point, and then back to the starting position.

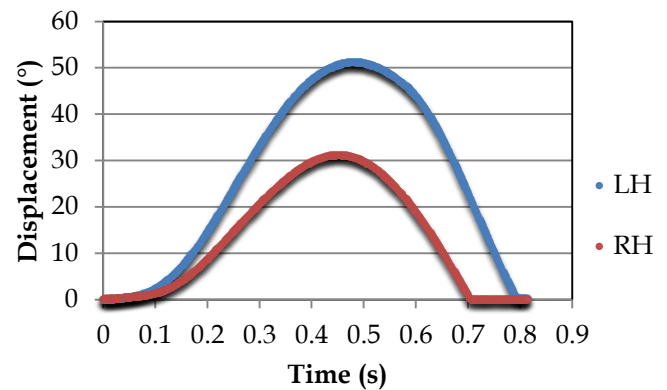


Figure 3. A sample displacement-time record from one participant from one trial from the 60°-20° test condition. LH is left hand and RH is right hand.

Protocol

The participants performed 20 practice trials in each of the 4 test conditions (20°-20°, 60°-60°, 20°-60° and 60°-20°) in an order determined randomly for each participant. Each trial began with the participant sitting in a standard chair in front of the apparatus and grasping the upper portion of the levers so that the upper arms were vertical and the elbow joints were 90°. On a brief single auditory stimulus, the participant attempted to move the levers to the goal reversal points and back to the starting position. Five seconds after completing the movement, the experimenter gave knowledge of results (KR) about the accuracy of each of the reversal points to the nearest degree. Bandwidth KR (12) with a 10% window was used to provide MT feedback since temporal error was not a focus of the current study. Accordingly, participants were given only qualitative KR about MT ("Too slow" or "Too fast") if the MT from any movement was greater than 770 ms or less than 630 ms, respectively.

Statistical Analysis

Spatial accuracy was determined from the potentiometer output by computing the constant error (CE) in the reversal point for

each movement over each set of 20 trials. Constant error indexes the average amount of overshooting or undershooting relative to the goal distance. For example, if a participant averages 18° over a set of trials with a goal of 20° , the CE would be -2° . Overshoots would result in positive CEs. The CE from the same- and different-distance conditions were compared with separate one-way ANOVAs with repeated measures on condition for the short distance (20° - 20° , 20° - 60° , 60° - 20°) and for the long distance (60° - 60° , 20° - 60° , 60° - 20°). In addition, a total assimilation index (TAI) was computed by summing the amount of overshooting of the shorter distance target in the different-distance conditions relative to the same-distance conditions with the amount of undershooting of the longer distance in the different-distance conditions relative to the same-distance conditions. For example, if a participant overshoot the 20° target by 4° more in the 20° - 60° condition than the 20° - 20° condition, and undershot the 60° target by 3° more than the 60° - 60° condition, the total assimilation index would be sum of the absolute differences, or 7° .

In order to describe the individual differences in the performance of the tasks, each practice trial was categorized using CE scores from each movement. If both movements were overshoot or undershot, these trials were classified as "paired." If one target was overshoot and the other target undershot, these trials were classified as "assimilated." The number of trials in each category were summed for each participant, converted to percentages, and analyzed with a 4 (Condition) \times 2 (Trial type) ANOVA with repeated measures on both factors. In addition, the reversal points produced in the hands were correlated across the 20 practice

trials. These Pearson's correlations (r) were converted to Fisher's Z scores and analyzed with a one-way ANOVA with repeated measures on Condition (20° - 20° , 60° - 60° , 20° - 60° , 60° - 20°). The Z scores were converted back to r for presentation.

In order to determine the factors that may underlie the total assimilation index, the TAI was correlated with the LQ, and the number of assimilated trials in the 20° - 60° and 60° - 20° conditions. Moreover, when means are reported in the results, they are listed with standard errors.

RESULTS

There was no difference between the CEs for the left hand ($1.83^\circ \pm 0.57^\circ$) and the right hand ($1.87^\circ \pm 0.54^\circ$) for the 20° - 20° condition, ($p = .93$), so the scores were averaged across side to compare with the different-distance conditions. There was no difference between the CEs for the left hand ($-2.88^\circ \pm 0.60^\circ$) and the right hand ($-1.96^\circ \pm 0.58^\circ$) for the 60° - 60° condition, ($p = .23$), so the scores were averaged across side to compare with the different-distance conditions.

Figure 4 shows the CEs for both the 20° and 60° movements for the same- and different-distance conditions. As expected, the 20° target was overshoot and the 60° target was undershot. The effect of condition was significant for the 20° distance, $F(2, 38) = 10.95$, $p < .001$, $\eta_p^2 = .36$. Paired post-hoc tests with a Bonferroni adjustment for multiple comparisons showed that the overshooting was greater in the 20° - 60° condition ($p < .01$) and the 60° - 20° condition ($p < .01$) compared to the 20° - 20° condition. The effect of condition was significant for the 60° distance, $F(2, 38) = 3.59$, $p < .05$, $\eta_p^2 = .16$.

Paired post-hoc tests with a Bonferroni adjustment showed that the undershooting was greater in the 20°-60° condition ($p < .05$) but not the 60°-20° condition ($p < .09$) compared to the 60°-60° condition.

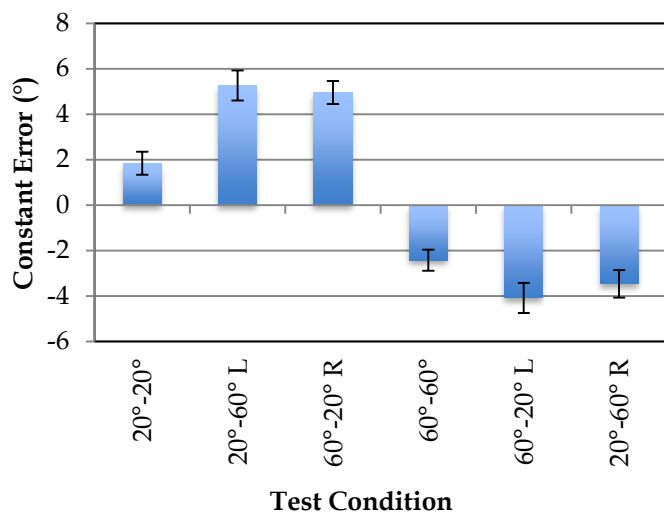


Figure 4. The CEs for both the 20° and 60° movements for the same- and different-distance conditions. L refers to the left hand and R refers to the right hand.

Figure 5 shows the individual differences in the TAI. Sixteen of the twenty participants showed total assimilation effects ranging from 2° to 30°. Four participants did not show assimilation effects, with total scores being zero or negative. The correlation between the TAI and the LQ was $-.10$ ($p = .35$).

Figure 6 shows the average reversal point correlations for the same- and different-distance conditions. There were strong, positive correlations between the reversal points for the same-distance conditions and low, positive correlations for the different-distance conditions. The effect of condition was significant, $F(1, 19) = 113.42$, $p < .001$, $\eta_p^2 = .87$. Paired post-hoc tests with a Bonferroni

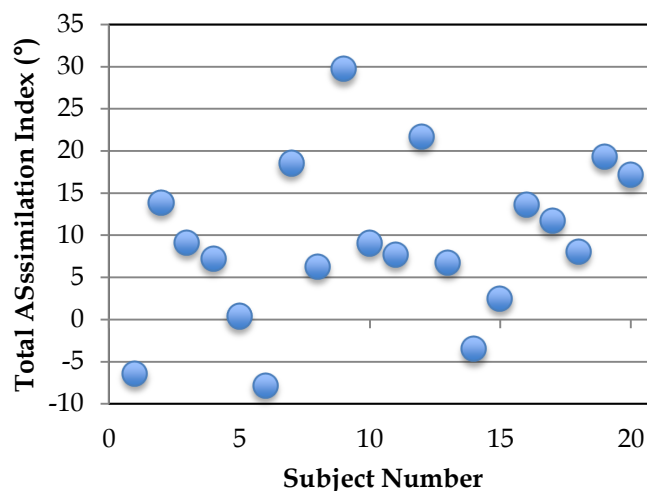


Figure 5. The individual differences in the total assimilation index.

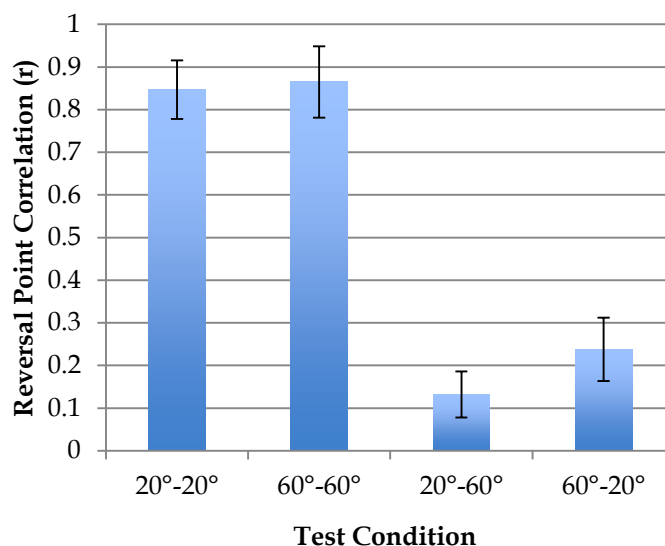


Figure 6. Average reversal point correlations for the same-distance conditions (20°-20°, 60°-60°) and the different-distance conditions (20°-60°, 60°-20°).

adjustment showed that the correlations were greater in the same-distance conditions compared with the different-distance conditions (all $ps < .001$). Individual differences in the correlations are shown in Figure 7. The amplitude correlations ranged from .55 to .95 for the same-distance conditions, and from $-.15$ to .54 for the different-distance conditions.

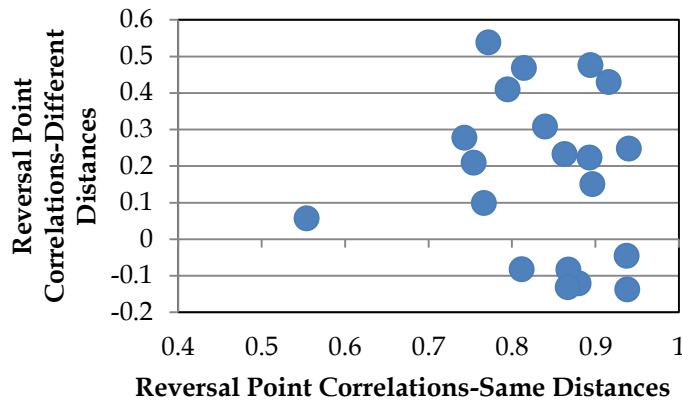


Figure 7. Individual difference in the reversal point correlations for the same-distance conditions (20°-20°, 60°-60°) and the different-distance conditions (20°-60°, 60°-20°).

Figure 8 show the percentage of practice trials classified as “paired” or “assimilated” for each condition. For the same-distance conditions, the ratio of paired to assimilated trials was 78% to 22%. In the different-distance conditions the ratio of paired to assimilated trials was 36% to 64% for the 20°-60° condition and 44% to 56% in the 60°-20° condition. The difference between the percentages in the same- and different-distance conditions resulted in a significant Condition \times Trial type interaction, $F(3, 57) = 57.14, p < .001, \eta_p^2 = .75$. Paired post-hoc tests with a Bonferroni adjustment showed that the number of paired trials was greater in both same-distance conditions compared with both different-distance conditions ($ps < .001$). The effect of trial type was also significant, $F(1, 19) = 27.65, p < .001, \eta_p^2 = .59$.

The individual differences in the proportions of each trial type are shown in Figure 9. The range in the proportions of assimilated trials for the same-distance condition was from 8% to 35%, and was 43% to 95% for the different-distance condition. The correlation between the number of assimilated trials in the same- and different-

distance conditions was .34 ($p = .17$). The correlation between the number of assimilated trials in the 20°-60° condition and the TAI was .41 ($p = .045$). The corresponding correlation between the 60°-20° condition and the TAI was .27 ($p = .14$).

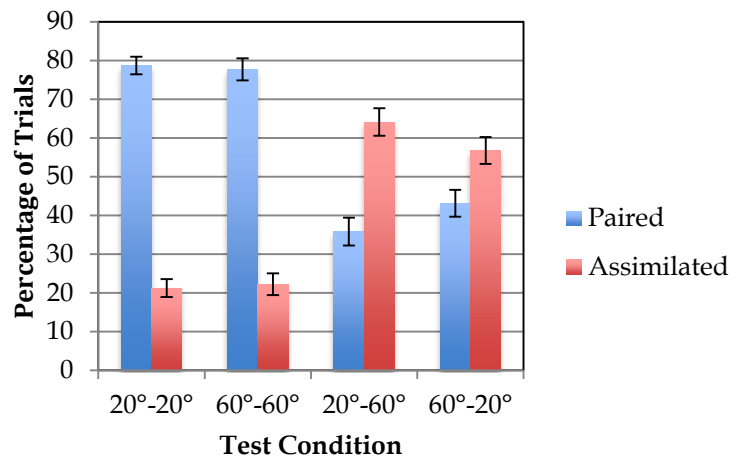


Figure 8. The percentage of paired and assimilated trials for the same-distance conditions (20°-20°, 60°-60°) and the different-distance conditions (20°-60°, 60°-20°).

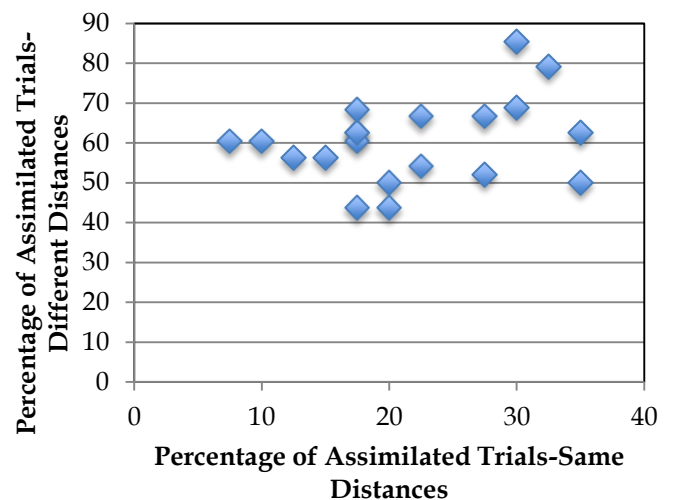


Figure 9. The individual differences in the percentages of paired and assimilated trials for the same- distance conditions (averaged across the 20°-20° and 60°-60° conditions) and the different-distance conditions (averaged across the 20°-60° and 60°-20° conditions).

DISCUSSION

The main goal of the current study was to identify individual differences in the motor programming process when participants produced bimanual aiming movements over the same or different distances. As expected, spatial assimilation effects were shown in the different-distance conditions relative to the same-distance conditions, with overshooting of the 20° target and undershooting of the 60° target replicating earlier work on bimanual control (15, 16, 24). The mean results clearly support Marteniuk and MacKenzie's model of two-hand control (4). According to the model, the lack of assimilation effects in the same-distance conditions are due to the same spatial scaling parameter being applied to each limb resulting in similar amplitudes in each hand. Additional support for the model is shown by the strong, positive, reversal point correlations in the same-distance conditions, showing that both targets were overshoot, or both undershot in tandem over the practice trials. These correlations also suggest that the same amplitude parameter was applied to both limbs in the same-distance conditions. The high percentage of paired trials in the same-distance conditions also supports the notion of common programming in both hands.

The assimilation effects in the different-distance conditions are likely due to the interaction between the shorter and longer amplitude scaling parameters as explained by Marteniuk, MacKenzie, and colleagues (4, 5). The overshooting of the shorter distance target and the undershooting of the longer distance target could both be caused by the interaction of the shorter and longer scaling parameters intended for each limb. It

is also not surprising to find a greater percentage of assimilated trials in the different-distance conditions compared with the same-distance conditions, and lower reversal point correlations as well.

Even though the mean results indicated the presence of spatial assimilation effects there were substantial individual differences in all of the dependent measures. For example, there was a wide variation in the total assimilation index across participants, with 4 participants not showing assimilation effects, and the remaining participants showing total assimilation effects between 2° and 30° (Figure 5). Clearly, subjects not showing assimilation effects were able to produce accurate responses in the different-distance conditions, and according to Marteniuk and MacKenzie's (4) model, they were able to prevent crosstalk from the opposite hand from interfering with the motor programming process. On the other hand, the participants showing greater assimilation effects were unable to prevent crosstalk from the opposite hand resulting in greater errors compared with those individuals showing smaller assimilation effects. One possibility is that the magnitude of the assimilation effects was directly related to the number of assimilated trials during the different-distance conditions, which varied greatly across participants (Figure 9). However, the TAI showed only low to moderate correlations with the number of assimilated trials in the different-distance conditions. Apparently, the TAI was affected by the magnitude of the assimilations rather than the number of assimilated trials.

Based on the mean assimilation effects shown in the different-distance conditions

one would expect negative correlations between the reversal points and expressly assimilated trials. Surprisingly, most of the reversal point correlations from the different-distance conditions were positive, not negative. Figure 10 shows data from one participant from the 20°-60° condition with a total assimilation index of 13°, but a reversal point correlation of .58. The figure clearly shows greater overshoots of the 20° goal were associated with longer movements in the opposite hand, even though most of the longer movements undershot the 60° target. The shorter movements toward the 20° goal still overshoot the target, but were associated with shorter movements in the opposite hand.

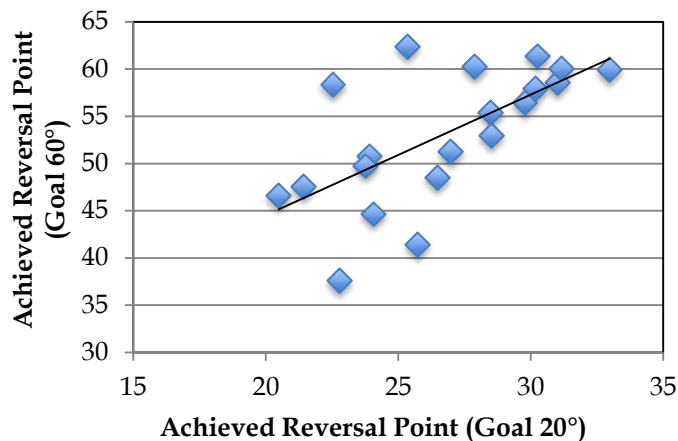


Figure 10. Reversal points for all trials for one participant in the 20°-60° condition.

Moreover, means and correlations provide unique information about performance. The mean assimilation effects reflect the average amount of interference between the hands, while the correlations provide information about the underlying programming strategies. For example, the strong, positive correlations in the 20°-20° and 60°-60° conditions and the high percentage of paired trials suggest that the same amplitude parameter was applied to both hands during

practice resulting in very little interference between them. During the different-distance conditions, participants were able to provide unique amplitude parameters to each hand, but the interaction between the parameters likely caused interference resulting in assimilation effects, reduced reversal point correlations, and more assimilated trials. However, the fact that 30-40% of the trials in the different-distance conditions were paired suggests that the control strategies employed during the same-distance condition were also employed to some extent in the 20°-60° and 60°-20° conditions.

The current study clearly indicates that there were two modes of control employed by the participants. On the paired trials, the participants used what might be called a "non-compensatory" mode whereby both targets were either undershot or overshoot. According to motor programming theory, these participants used amplitude parameters that were either too large or too small for both of the hands resulting in overshooting or undershooting in both hands, respectively. According to Marteniuk and MacKenzie's theory (4) participants were able to prevent crosstalk between the hands on these trials, allowing the originally programmed amplitude parameters to affect the movement outcome. On the assimilated trials, participants used what might be called a "compensatory" mode, where they overshoot the 20° movement, but undershot the 60° movement. On those trials when the compensatory mode was used, the shorter amplitude parameter was biased by the longer amplitude parameter resulting in the use of an incorrect parameter value and overshooting of the 20° target. The longer amplitude parameter was also biased by the shorter distance parameter resulting in

undershooting of the 60° target. The trial-to-trial variability shown here by the participants demonstrates the dynamic nature of the response programming process. On any given practice trial, the amplitude parameters might react in a negative way resulting in overshooting of one movement and undershooting of the other. On another trial, the parameters could be positively biased, so that both parameters are greater, or smaller than planned, resulting in overshooting or undershooting of both movements. However, the data suggest that participants did not necessarily use the same strategy for both the same- and different-distance conditions. The correlation between the number of assimilated trials in the two conditions was positive, but low (i.e., $< .4$), suggesting that the same strategy was not used on a consistent basis in all test conditions.

The trial-to-trial variability in the response programming process could be due to a number of factors. Because KR was provided after each trial, participants ideally used this information to try to correct their errors on the next movement (8). Therefore, if both targets were overshoot on one trial, both targets may have been undershot on the next trial. In addition, if there was a greater error in one hand than the other, an effort might have been made to correct the largest error on the next trial. Another factor that could contribute to the variability across trials is the change in the attentional focus of the participants. For example, one could focus their attention on one of the hands more so than the other, in an effort to reduce an error in that hand from the previous trial. Research has shown that movement accuracy is better when focusing attention

on a given hand relative to the other hand in bimanual aiming movements (27).

It is clear from this and earlier work that accuracy in aiming movements depends on a number of factors. When single aiming movements are made spatial accuracy depends primarily on movement distance and movement time (10, 11, 32). However, the resulting accuracy of bimanual aiming movements is not only due to the kinematic goals of the movement (i.e., distance and movement time), but also to the movement goals of the opposite hand. In addition, both compensatory and non-compensatory modes were used by participants in dealing with the challenges of controlling rapid movement sequences.

The individual differences shown in the current study could help explain why some individuals have difficulty learning and performing sequential motor skills like piano or guitar playing. Sixteen of the participants showed assimilation effects on the different-distance practice trials, indicating difficulty in preventing interference from one hand to the other. At the same time, a significant proportion of the trials showed the non-compensatory mode, with overshooting or undershooting on both movements, depicting the difficulty of programming the precise parameters necessary for accurate performance. Additionally, the LQ was not significantly correlated with the amount of assimilation, at least in right-handed subjects, suggesting that the level of handedness preference had no effect on the amount of assimilation. The main limitation of the study was that handedness was the only individual difference variable assessed in our sample. Future studies could assess past musical,

artistic, and/or athletic activities and prior health status, for example, to determine how past experience relates to the accuracy in bimanual movements.

Finally, in order to reduce assimilation effects, a number of practice strategies could be employed. For example, practicing with concurrent visual feedback has been shown to reduce assimilation effects in movement sequences (12,22, 23, 26) as well as reducing movement speed (18), or using part practice techniques (28, 29). With enough deliberate practice such assimilation effects should be overcome (1).

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