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Does Handedness Determine Which Hand Leads in a Bimanual Task?

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ABSTRACT. Right- and left-handers (n = 16 in each group) were tested on a bimanual circle task that required drawing either in the same direction (parallel) or in a mirror symmetrical coordination mode with the two hands. The authors' primary purposes were to examine the effect of circle direction on within-hand and between-hands variables and to determine whether the relation between hand lead and coordination mode (parallel or mirror symmetrical) differs for left- and right-handers. A strong relation was found between lead hand and movement condition, which depended on the direction of the movements and whether the task was parallel or mirror symmetrical. The pattern of results was similar for left- and right-handers on parallel tasks, but group differences were found with respect to mirror symmetrical tasks. At odds with the general claim that the dominant hand leads, the present results indicated that hand dominance does not generally determine which hand leads.

Key words: bimanual, handedness, motor control

In the literature on bimanual coordination, considerable interest has been paid to the phase difference between hands (i.e., Kelso, Scholz, & Schöner, 1986; Scholz & Kelso, 1989; Swinnen, Jardin, & Meulenbroek, 1996; Wuyts, Summers, Carson, Byblow, & Semjen, 1996). If one hand leads the other, the lead hand will pass a point on its trajectory before the lag hand passes the same point on its respective trajectory. Those differences in time can similarly be expressed with respect to the angular difference traversed by each hand, with 360° referring to one full cycle. In that terminology, at a specific moment in time, the lead hand has traversed a larger angular distance with respect to its cycle of movement than the lag hand with respect to its cycle of movement. Assuming the tasks for the two hands are identical, if the total cycle duration of a movement is known, then the phase difference with respect to time can be converted into the phase difference with respect to angular distance, and vice versa.

Phase relations in continuous tasks performed by neurologically normal participants have been studied quite extensively. In this article, we focus specifically on the task of continuous bimanual circle drawing. Individuals can draw bimanual circles by using clockwise (CW) movements of one hand in combination with counterclockwise (CCW) movements of the other, comprising two possible mirror symmetrical modes of coordination. Alternatively, circles can be drawn in a parallel manner, with both hands moving in the same direction, comprising two mirror asymmetrical modes of coordination. The primary focus in recent examinations of neurologically intact individuals' performance of that task has been on the differences in phase relations of mirror symmetrical and parallel movements. Generally, parallel movements are not as stable as mirror symmetrical movements (Carson, Thomas, Summers, Walters, & Semjen, 1997; Semjen, Summers, & Cattaert, 1995; Stucchi & Viviani, 1993; Swinnen, Jardin, Meulenbroek, Dounskaia, & Hofkens-Van Den Brandt, 1997). That conclusion was based on two primary findings. First, the phase difference between hands is generally smaller with mirror symmetrical than with parallel movements. Second, the variance of the between-hands lag is smaller with mirror symmetrical than with parallel movements. In addition to those primary characteristics, the nondominant hand tends to produce slightly less accurate and more variable trajectories than the dominant hand (Carson et al., 1997; Semjen et al., 1995; Stucchi & Viviani, 1993).

Another intriguing question arises from the literature on phase differences. Which hand tends to lead in a bimanual

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motor task—the right or the left? One possibility is that the dominant hand tends to lead the nondominant. Accordingly, the right hand would lead in right-handers, and the left hand would lead in left-handers. In one investigation related to that issue, Stucchi and Viviani (1993) focused on cerebral dominance in the timing of bimanual ellipse drawing. They instructed both left-handers and right-handers (n = 10 in each group) to trace ellipses in the space in front of the body, at the approximate tempo indicated by a train of auditory stimuli presented just before each recorded trial. Parallel and mirror symmetric conditions were examined. The investigators reported that the dominant hand consistently led the nondominant hand by approximately 20 ms on average in both left-handers and right-handers.

Semjen et al. (1995) tested 4 participants, of whom 2 were left-handed according to self-report. Their task was similar to that of Stucchi and Viviani (1993), except that circles were drawn at either a preferred rate or as fast as possible and visual templates that indicated circle size were used. Semjen and colleagues also reported that the dominant hand tends to lead the nondominant hand, although that pattern was not as consistent as the one reported by Stucchi and Viviani.

Swinnen et al. (1996) tested left-handers and right-handers (n = 10 in each group) on bimanual circle drawing under free-vision conditions (no specific instructions about where to focus), with visual monitoring of one hand, or blindfolded. The movements were performed in pace with a metronome; in visual conditions, a template indicating circle size was used. Swinnen and colleagues reported that the dominant hand tended to lead the nondominant hand and that the phase difference was larger in right-handers than in left-handers. Phase difference also differed as a function of viewing condition, being largest with visual monitoring of the dominant hand, intermediate in magnitude under free vision and blindfolded conditions, and smallest with visual monitoring of the nondominant hand. In addition, there was some evidence of a less consistent hand lead pattern in left-handers.

Across studies on bimanual circle drawing, there appears overwhelming support for the claim that the dominant hand leads the nondominant hand. As described earlier, that conclusion stems from experiments in which participants were required to trace visual templates, to follow a metronome pace, or both. In either case, the requirement to follow an auditory stimulus or view a visual template might have influenced the patterns of lead hand. Indeed, Swinnen et al. (1996) provided one demonstration that relative phase changes with different conditions of visual monitoring.

In the present article, we examined whether the dominant hand was the lead hand in bimanual circle drawing conditions in which no form of visual monitoring and no auditory pace were used. We examined four conditions of bimanual circle drawing in right-handers and left-handers under conditions of no direct vision of the hands. Movements were performed at a preferred (self-selected) pace and circle size. Consistent with past studies, those conditions included mirror symmetrical drawing in two possible directions and parallel drawing in two possible directions. The predictions were straightforward: If the dominant hand is the lead hand in the drawing task, then the right hand would be expected to lead in right-handers and the left hand would be expected to lead in left-handers. Conversely, if the same rather than the directly opposite pattern of lead hand characterizes performance of left-handers and right-handers, then it would appear that handedness does not generally determine lead hand. We were particularly interested in the latter possibility and whether coordination mode (mirror symmetrical or parallel) alone or in combination with movement direction (CW or CCW) might be better predictors of lead hand.

We reasoned that one could use any similarities across the pattern of results of left-handers and right-handers to infer general properties of bimanual circle drawing, irrespective of handedness. Any differences in the pattern of results across the two groups could be interpreted as reflecting properties related to correlates of handedness. To briefly preview our main findings, we observed that the patterns of lead hand depended on the direction of movement of the left and right hands when movements were performed in the same direction (referred to as *parallel*). Clockwise circles tended to be characterized by a right hand lead, and counterclockwise circles tended to be characterized by a left hand lead, in both left-handers and right-handers. When circles were drawn with mirror symmetry (the two hands drawing in opposed directions), the right hand tended to lead in right-handers and the lead hand was mixed in left-handers (some trials, right hand lead, and some trials left hand lead). Those findings leave open the possibility that handedness plays a role in determining lead hand on mirror symmetrical tasks. Those findings will be discussed following a thorough description of experimental data collected on large groups of right-handers and left-handers.

Method

Participants

The right-handed group consisted of 16 participants (8 men and 8 women) ranging in age between 17 and 30 years (M = 21.5, SD = 5.6) from the University of Otago Department of Psychology participant pool. All were right-handed by self-report. In addition, all displayed a score indicating strong right-handedness on the Oldfield (1971) inventory. The mean score for the group was .64 (SD = .03), on a scale ranging from −1.0 (strongly left-handed) to 1.0 (strongly right-handed).

The left-handed group consisted of 16 participants (7 men and 9 women) ranging in age between 17 and 30 years (M = 20.0, SD = 3.0) from the same participant pool. All were left-handed according to self-report, and the group mean on the Oldfield (1971) inventory was −.61 (SD = .05).

Apparatus and Task

Two digitizer tablets (30 × 30 cm) were interfaced with a portable laptop computer. The tablets record the *x* and *y* coordinates of motions of hand-held magnetic pens at 80 samples per second, with a spatial resolution of .0025 cm. The pens do not leave a visible trace. The participant sat facing a table on which the tablets were placed side by side, with the boundary between tablets aligned with the participant's nose. The participant visually focused on a point located at approximately a 45° angle from horizontal eye level on the wall straight ahead so that direct vision of the hands would not be possible. An experimenter monitored each participant throughout the entire testing session to make sure his or her eyes remained focused on the specified point and to ensure that all procedures were carried out correctly.

Design and Procedure

Following two blocks of unimanual drawing for practice, four blocks of bimanual circles were performed at a preferred speed within the spatial boundary of the digitizer tablets. The four bimanual conditions were counterbalanced. Participants were instructed to begin to draw at approximately the top of the circles (the 12 o'clock point) and in the specific directions depicted by the experimental condition. The four conditions were (a) clockwise, parallel with both hands (+,+); (b) counterclockwise, parallel with both hands (–,–); (c) mirror symmetrical, clockwise with the left hand and counterclockwise with the right (+,–); and (d) mirror symmetrical, counterclockwise with the left hand and clockwise with the right (–,+).

Each block consisted of eight consecutive trials lasting 8 s each. The recording apparatus began collecting data just after the participant began to draw. We gave rest between trials as needed to minimize fatigue. Between blocks of trials, 2 min of rest filled with irrelevant conversation were given. Each testing session lasted approximately 30 min.

Data Reduction and Analysis

The analysis developed in this article was built on kinematic methods for computing continuous phase across trajectories that might not form perfect circles or revolve around a stable center. In the algorithm, one uses tangential angle (TA) to individually associate every point on the trajectory with an approximately 360° circle (see Appendix). One then uses each circle to calculate an instantaneous value of period, radius, angle of displacement, and eccentricity for its associated point. We repeated the following process to generate those measures for every point on the trajectory.

The period is calculated as the time between start and endpoint of the circle. To calculate the radius, one first defines the circle center as the midpoint of the *x* and *y* values bounded by the circle. The radius is then calculated as the distance between the associated point and the circle center. The angle of displacement refers to the orientation of a line (in degrees) drawn from the circle center to the associated point, using 12 o'clock as a reference.

As observed by other authors (Stucchi & Viviani, 1993), circular motions are often elliptical rather than perfectly circular, and that is usually the case when one draws without the use of a template. As an approximation of degree of circularity, we computed an aspect ratio. For each circle, we calculated the major axis by measuring the diameter at 5° steps to find the maximum diameter. By measuring the diameter orthogonal to the major axis, we calculated the minor axis. The aspect ratio was computed as the minor diameter divided by the major diameter. For a perfect circle, the aspect ratio would be 1.00. For an ellipse that is half as wide as it is long, the aspect ratio would be .5. We also computed eccentricity measures, using the standard computation specified in the Appendix. In the eccentricity measure, the distance between foci on the ellipse is taken into account, rather than considering each ellipse as strictly orthogonal component vectors.

For the between-hands measure of phase, the difference between the angles of displacement of the left and right hands was computed. For example, if at some point the left hand was at a 50° orientation and the right hand was at 35°, the phase difference would be a left hand lead of 15°. To maintain consistency with other studies, we converted the angular phase to a temporal phase difference by dividing it by 360° and multiplying by the instantaneous period (averaged across hands).

Finally, we derived the means of each within-hand measure (radius, period, and aspect ratio) and the between-hands measure (phase difference), in addition to a measure of variability (coefficient of variation, *CV*, or standard deviation, *SD*) for each. Full details of those calculations can be found in the Appendix.

We analyzed each within-hand variable by using separate mixed-effects repeated measures analyses of variance (ANOVAs) to test the 4 (condition: parallel CW and parallel CCW; mirror symmetrical, right hand CW, left hand CCW; and mirror symmetrical, left hand CW, right hand CCW) × 2 (hand: left and right) × 8 (trial) within-hand variables and the 2 (group: right- vs. left-handers) between-participants variable.

The between-hands variables of interest included the signed mean phase difference, the unsigned mean phase difference (absolute values of phase taken before averaging), and the *SD* of phase. We analyzed each between-hands variable by using a separate mixed effects repeated measures ANOVA that tested the 4 (condition) × 8 (trial) within-participant variables and the 2 (group: right- vs. left-handers) between-participants variable. We applied post hoc comparisons by using Bonferroni corrections to disentangle main effects on condition. For all statistical analyses, significant effects at the $p < .05$ level are reported. For those effects that were not significant, we report p values only for analyses in which $F > 1$. For Fs < 1, we simply state that finding.

A qualitative analysis of the relationship between coordination mode, directional mode, and lead hand was also performed. Specific details of those analyses are discussed in turn.

Results

Representative plots of displacement and phase differences for 1 control participant can be seen in Figures 1 and 2 (for a mirror-symmetrical trial and a CCW parallel trial, respectively). As can be seen from both the *x* and *y* profiles (panels A and B) and the displacement versus time plots (panels C and D), movement was reasonably smooth throughout the trials and the trajectories approximated circles. There were very small phase differences in the mirror symmetrical tasks, as shown by the close overlap in the angular displacement versus time profiles (see Figure 1, panel E). The angular displacement versus time profiles for parallel tasks showed a phase lead of one hand relative to the other (see Figure 2, panel E). The instantaneous phase difference showed variability across each trial (panel F in both figures). For the mirror symmetrical trial shown, the average phase lead hovered around zero and produced a slight negative value on average, revealing a right hand lead (see Figure 1, panel F). For the CCW parallel task, the average phase lead was positive, indicating a left hand lead (see Figure 2, panel F).

Within-Hand Variables

Radius

The overall mean radius across all participants was 6.53 cm (SE = .47). The mean for right-handers (7.45 cm, SE = .67) was marginally larger than the mean for left-handers

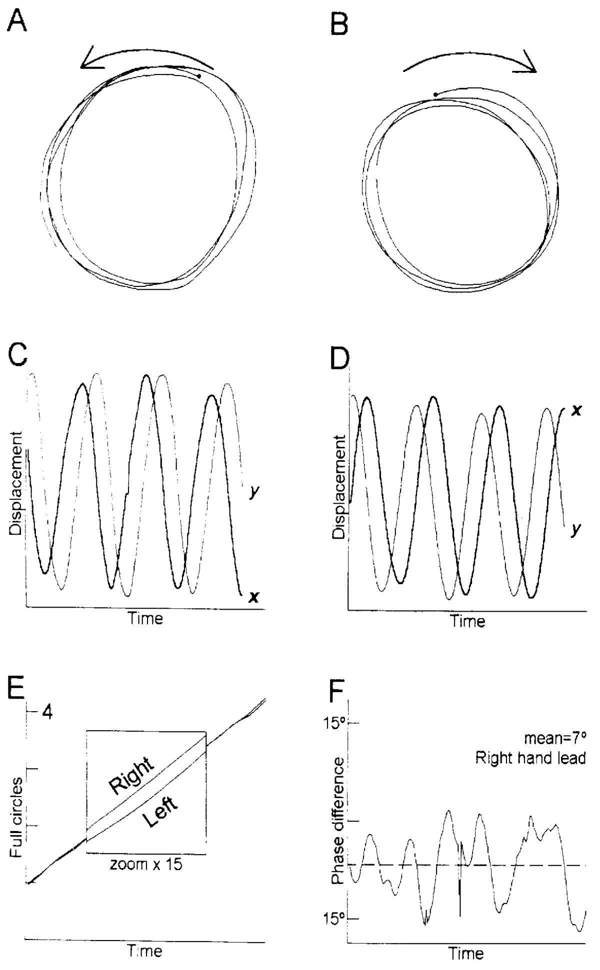

FIGURE 1. Plots of one trial in the mirror-symmetrical (–,+) condition for a representative participant. Displacement (cm) in *x* versus *y* is shown for 6 s of the trial for the left (**A**) and right (**B**) hands. For the left hand (**C**) and right hand (**D**), displacement versus time (ms) is also shown. (**E**) Cumulative displacement in angular degrees across time (ms) is depicted for both hands, with a 15× zoom window, showing that the right hand leads the left. (**F**) Instantaneous phase differences between hands in angular degrees across time (ms) are shown. The dashed line shows that mean phase difference was negative, verifying a right hand lead.

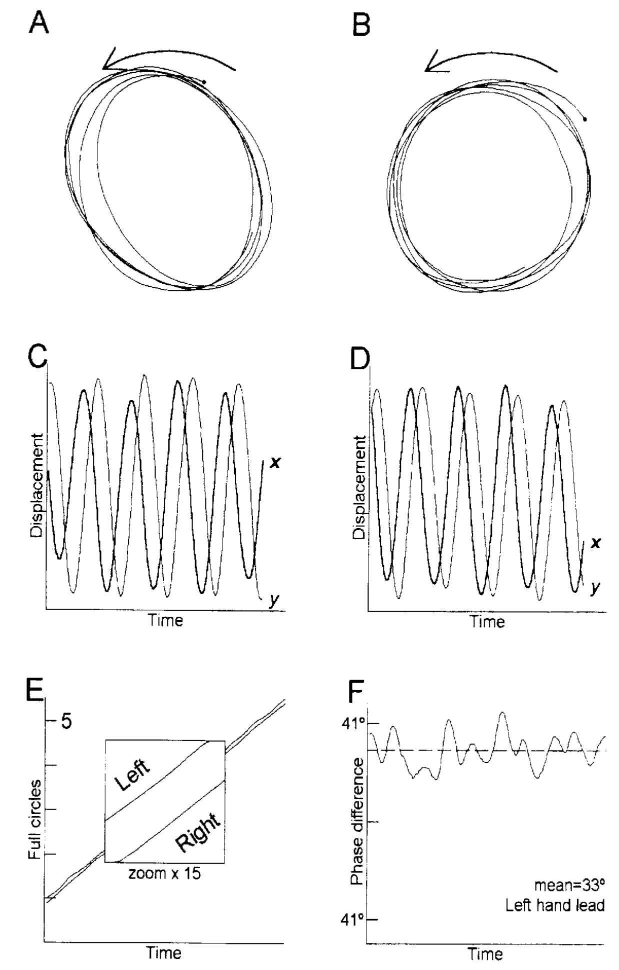

FIGURE 2. Plots of one trial in the parallel (–,–) condition for the same representative participant. Displacement (cm) in *x* versus *y* is shown for 6 s of the trial for the left (**A**) and right (**B**) hands. For the left hand (**C**) and right hand (**D**), displacement versus time (ms) is also shown. (**E**) Cumulative displacement in angular degrees across time (ms) is depicted for both hands, with a 15× zoom window that shows that the left hand led the right. (**F**) Instantaneous phase differences between hands in angular degrees across time (ms) are shown. The dashed line shows mean phase difference to be positive, verifying a left hand lead.

(5.6 cm, SE = .67), $F(1, 30) = 3.84$, $p = .059$. That difference was not expected, nor is there any known theoretical justification for it. The main effect of condition on mean radius was not significant, $F(3, 90) = 2.01$, $p = .118$, and condition did not interact significantly with group, $F < 1$.

Hand produced a significant main effect on mean radius, with a larger average circle radius for the left hand (M = 6.68 cm, SE = .48) than for the right (M = 6.38 cm, SE = .47), $F(1, 30) = 14.31$, $p < .001$. Hand did not interact with group, indicating that the same basic pattern of results was produced for left-handers and right-handers, $F(1, 30) < 1.00$. The interaction of condition and hand was significant, $F(3, 90) = 9.64$, $p < .001$. The pattern of that interaction revealed that the left hand always produced larger average radii than the right, and the difference in size between the two hands was largest in the (–,–) condition (mean difference = .57 cm), as compared with the other conditions (mean differences ranged from .10 to .34 cm). Most notable, no instructions were given as to the specific size of circles, so those effects on radius were unexpected.

A main effect of trial indicated that the average radius became slightly smaller as the trials progressed (Trial 1 mean = 6.76 cm, Trial 8 mean = 6.48 cm), $F(7, 210) = 8.28$, $p < .001$. The two-way interaction of condition and group was not significant, nor was the two-way interaction between trial and group (both $ps > .05$). There was a significant three-way interaction of condition, hand, and trial, but the pattern of that interaction was not meaningful, $F(21, 630) = 3.537$, $p < .001$. No other significant main effects or interactions were found for mean radius (all $ps > .05$).

There was a significant main effect of condition on the CV radius, $F(3, 90) = 2.78$, $p = .046$. Observation of the means that produced that effect indicated that the actual differences were very slight (ranging from .083 to .091). Because there was no apparent pattern underlying that main effect on CV radius and the magnitude of the effect was quite small, we have not interpreted that finding further.

The Condition × Group interaction on CV radius did not reach significance, $F(3, 90) = 1.53$, $p = .212$, indicating that the variance of circle radii was not reliably different for left-handers and right-handers, on average. There was also no main effect of hand ($F < 1.0$). However, the two-way interaction of hand and group was highly significant, $F(1, 30) = 41.27$, $p < .001$. The interaction on CV radius indicated that, on average, the radii produced by the nondominant hand (CV radius = .10) were more variable than the radii produced by the dominant hand (CV radius = .075). There were no other significant main effects or interactions on CV radius (all $ps > .05$).

In sum, effects on mean radius indicated that, on average, the left hand drew larger circles than the right. That effect was similar for left-handers and right-handers. For the CV radius, the primary effect was that the dominant hand produced less variable circle radii than the nondominant hand. The effect was also similar for left-handers and right-handers.

Period

The grand mean period was 1,289 ms (SE = 67). The main effect of condition on mean period was significant, $F(3, 90) = 3.263$, $p = .025$. The mean period for both parallel conditions (+,+ and –,–) was 1,310 ms (SE = 71 and 68, respectively). The main effect of condition was the result of a shorter mean period for the mirror symmetrical (+,–) condition (M = 1,245 ms) than for all other conditions; all $Fs(1, 30) > 6.29$, all $ps < .01$. The mean for the mirror symmetrical (–,+) condition was 1,291 ms. Because one mirror symmetrical condition (+,–) differed from both parallel conditions but the other mirror symmetrical condition (–,+) did not, those apparent differences in mean period might not be too revealing.

There was a significant main effect of hand on mean period, but that amounted to only 2-ms difference between hands, $F(1, 30) = 6.84$, $p = .014$. Hand also interacted significantly with group, revealing a slightly shorter mean period for the dominant than for the nondominant hand for both left-handers and right-handers, $F(1, 30) = 41.07$, $p < .001$. In addition, there was a significant two-way interaction between condition and hand, $F(3, 90) = 2.92$, $p = .038$. However, that interaction did not produce a meaningful pattern. Of primary importance, the main effect of group on mean period was not significant, $F(1, 30) = 1.205$, $p = .281$, nor was the Condition × Group interaction, $F(3, 90) = 1.557$, $p = .205$.

For the CV period, there was a highly significant two-way interaction of Hand × Group, $F(1, 30) = 17.75$, $p < .001$. The interaction revealed that the period was more variable for the nondominant than for the dominant hand in both left- and right-handers.

In sum, the effects on mean period indicated that whereas some conditions produced a slightly shorter period than others, the differences appeared to be inconsequential. The same basic effects were found for left-handers and right-handers. A reliable effect was that the dominant hand produced a slightly shorter mean period than the nondominant hand for both groups. A similar effect was found for the CV period, with a more variable period for the nondominant hand in both groups.

Aspect Ratio and Eccentricity

The grand mean was .837 (SE = .004), where 1.00 would be a perfect circle. There was a significant main effect of condition on the mean aspect ratio, $F(3, 90) = 3.376$, $p = .022$. However, the maximum difference in the mean aspect ratio between any two conditions amounted to only .02, suggesting that those differences were very slight. Post hoc comparisons further revealed that the mirror symmetrical (+,–) condition produced a slightly smaller aspect ratio than the two parallel conditions, a somewhat curious effect (both $ps < .01$). The only other statistically significant effect was the Hand × Group interaction, $F(1, 30) = 26.96$, $p < .001$. That interaction revealed that the nondominant hand produced slightly less-circular shapes than the dominant hand in both left-handers and right-handers. There were no other significant main effects or interactions on the mean aspect ratio (all $ps > .05$).

For aspect ratio *SD*, the main effect of condition was not significant, indicating that the variance of the aspect ratio was not reliably different across modes of drawing, $F(3, 90) = 1.57$, $p = .203$. The Condition × Hand interaction was highly significant, but the pattern of that interaction was not meaningful, $F(3, 90) = 4.14$, $p = .009$. A significant interaction between hand and group revealed that the nondominant hand produced more variability in the aspect ratio than the dominant hand, on average, $F(1, 30) = 78.87$, $p < .001$.

The grand mean eccentricity was .520 ($SE = .007$). Mean eccentricity differed only by .02 between any two conditions. Statistical analyses revealed the same pattern of significant results as that found for aspect ratio (a main effect of Condition, and a Hand × Group interaction, both $ps < .05$). Thus, the primary results were captured by the thorough analysis of aspect ratio described earlier. In sum, the mean aspect ratio measure indicated that circles were slightly elliptical in all conditions. The primary results of those analyses revealed that circles produced by the dominant hand were slightly more circular and less variable than circles produced by the nondominant hand.

Between-Hands Variables

Mean Signed Phase

The grand mean signed phase difference was −1.721 ($SE = 1.74$), indicating a slight right hand lead, on average. The two groups combined produced a highly significant main effect of condition on mean phase, $F(3, 90) = 27.94$, $p < .001$. Post hoc comparisons further revealed significant differences across all conditions (all $ps < .001$), except for the two mirror symmetrical conditions, which were approximately identical to one another, ($p > .05$). Of primary importance, the interaction between group and condition was not even close to being significant, $F(3, 90) = .469$, $p = .705$. In fact, the pattern of results across the four conditions was quite similar for left-handers and right-handers, as can be seen in Figure 3. For both handedness groups, the right hand led in the parallel CW condition, and the left hand led in the parallel CCW condition. On mirror symmetrical conditions, the right hand primarily led in right-handers. For left-handers, the phase difference was very close to zero on both mirror symmetrical conditions.

A significant Trial × Group interaction revealed that for left-handers, mean phase became gradually less negative through trials, and for right-handers, mean phase became gradually more negative through trials, $F(7, 210) = 7.57$, $p < .001$. The three-way interaction of condition, group, and trial was also significant, but the pattern of that interaction was not meaningful, $F(21, 630) = 1.818$, $p = .014$. There were no other significant main effects or interactions on mean phase (all $ps > .05$).

The analysis of *SD* phase revealed a main effect of condition, $F(3, 90) = 27.94$, $p < .001$. *SD* phase was approximately 7 ms for mirror symmetrical conditions and approximately 11 ms for parallel conditions. Post hoc comparisons revealed that the two parallel conditions were not significantly different from one another, $F(1, 3) = 2.83$, $p = .10$, but each differed from both mirror symmetrical conditions (all $ps < .001$). The two mirror symmetrical conditions did not differ significantly from one another ($F < 1.0$). Those differences between parallel and mirror symmetrical conditions were consistent with those of mean phase, and those primary main effects were consistent with previous research (see introductory comments).

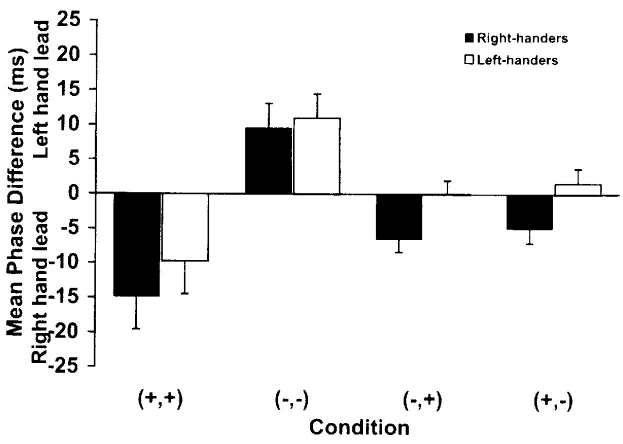

FIGURE 3. Mean phase difference and standard error (ms) for each bimanual condition in right- and left-handed participants.

Mean Absolute Phase

A close look at Figure 3 reveals that for right-handers, the right hand tended to lead in both types of mirror-symmetrical drawing. For left-handers, the average phase difference on the two mirror-symmetrical conditions was close to zero. Given that the values of phase difference could be positive (left hand lead) or negative (right hand lead), however, those averages might have reflected two different patterns of behavior. An average phase difference of zero might indicate that the hands were closely coupled and that the phase difference actually hovered around the zero point. Alternatively, the magnitude of phase difference could have been larger, but because each hand led on approximately half the trials (or half the total magnitude of the phase difference), the values could have canceled one another with averaging. To evaluate those possibilities, we computed the absolute value of phase difference on each trial before averaging. If the two computations (mean signed phase and mean absolute phase) resulted in similar values, then we could conclude that the average phase is a valid indicator that one hand led the other somewhat consistently. If the absolute value computation produced substantially larger values than the magnitude of the average phase difference, however, then it would appear that there was a mixed hand lead (i.e., some trials led by the left hand and some by the right). Such a finding would imply that phase differences that were opposite in sign canceled one another as a result of averaging.

The between-groups analysis for absolute phase revealed a highly significant effect of condition, $F(3, 90) = 18.12$, $p < .001$. Consistent with analyses on mean signed phase, comparisons between the two parallel conditions revealed that they were not statistically different from one another, $F(1, 30) = 1.68$, $p = .21$. Similarly, comparisons between the two mirror symmetrical conditions revealed no statistically reliable differences, $F(1, 30) < 1.0$. All analyses testing differences between parallel and mirror symmetrical conditions were statistically reliable (all $ps < .001$).

Of primary importance, the main effect of group was not statistically significant, indicating similar patterns for left- and right-handers, $F(1, 30) < 1.00$. The only other significant effect was a two-way interaction between condition and trial, $F(21, 630) = 2.26$, $p < .001$. That interaction revealed that in the parallel (+,+) condition, the absolute phase became gradually smaller from Trial 1 ($M = 24$ ms) to Trial 8 ($M = 16$ ms). Within each remaining condition, the absolute phase remained approximately the same across trials.

Relation Between Hand Lead, Coordination Mode, and Direction

To further investigate the relationship between mode of drawing and hand lead, we tallied the number of trials led by each hand for each condition. Across the 16 right-handed participants, 12 maintained a consistent hand lead across all trials within each condition. The remaining 4 participants maintained a consistent hand lead on all conditions except the mirror-symmetrical (+,–) condition, on which approximately half the trials were led by the left hand and half the trials were led by the right hand for each of the 4 participants. Thus, consistent lead hand effects were maintained almost perfectly across all conditions. For the left-handers, the two different computations of phase (see the preceding discussion) produced markedly similar values for both parallel conditions. For mirror-symmetrical conditions of left-handers, however, the absolute value computation led to values that were quite different from the (approximately) zero values produced in the direct computation of the averages. A closer look at the data from those participants indicated a strong mixed hand lead. For 11 of the 16 left-handed participants, neither hand consistently led throughout all trials of the same type, and the mean absolute value of the phase difference was approximately 7 ms. Thus, the values did not hover around zero; rather, positive and negative values canceled each other to produce an average of approximately zero. For the remaining left-handers, 3 produced a consistent right hand lead and 2 produced a consistent left hand lead across mirror symmetrical trials. Those results, together, indicate that there was a strong tendency for a mixed hand lead on mirror symmetrical trials in left-handers. In contrast, right-handers tended to lead with the right hand on mirror symmetrical trials. The percentage of trials characterized by each lead hand for both groups is shown in Figure 4. Of primary importance, the pattern of hand lead results for parallel tasks was similar across right-handers and left-handers but differed somewhat with respect to mirror symmetrical tasks.

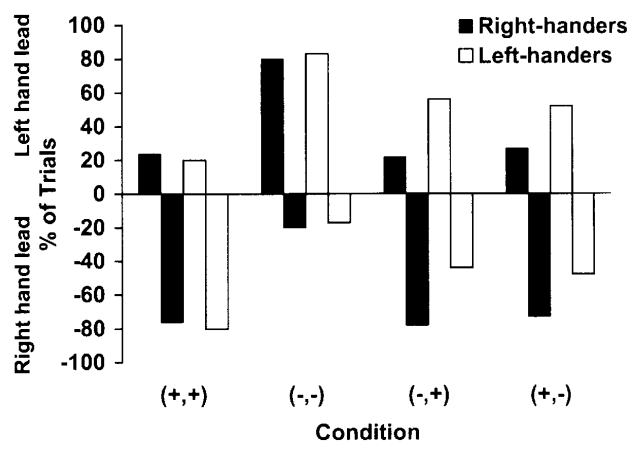

FIGURE 4. Proportion of trials with right hand lead (shown as negative) and left hand lead (shown as positive) for right- and left-handed participants across all bimanual conditions.

Discussion

We tested right- and left-handers on a continuous bimanual circle drawing task performed at a preferred pace and circle size and without direct vision of the hands. Our primary goal was to evaluate the claim that the dominant hand tends to lead the nondominant. Another specific goal was to assess whether consistent patterns of lead hand characterize the particular coordination modes and directional modes, an issue that has not been directly examined in previous work. We tested large groups of right- and left-handers in order to make direct comparisons between handedness groups. We also incorporated the novel feature of examining movements performed without the use of a visual template, an auditory pace signal, or vision of the hands. Our aim was to examine the effect of movement direction and coordination mode on within-hand and between-hands variables without the possible influence of those factors.

The pattern of results across participants revealed two findings of primary importance. First, in both left-handers and right-handers, the right hand tended to lead in CW parallel movements, and the left hand tended to lead in CCW parallel movements. The similarity of findings between groups indicates that handedness does not determine which hand leads in parallel tasks. Rather, coordination mode and movement direction appear to be the determining factors. The second finding of importance was that the right hand tended to lead in both conditions of mirror symmetrical drawing in right-handers, whereas a mixed hand lead was the tendency in left-handers on mirror symmetrical tasks. Accordingly, handedness might play a role in determining hand lead in mirror symmetrical tasks. Before elaborating on those primary findings, we discuss some specific findings based on within-hand and between-hands variables.

To enable readers to interpret the within-hand and between-hands effects with respect to our proposed hypotheses, we offer a reminder of some definitions. As noted earlier, handedness refers to where a person falls on a continuum that ranges from strongly left-handed to strongly right-handed, on the basis of hand preference on a battery of tasks (Oldfield, 1971). According to our analyses, those variables that are correlates of handedness tend to be revealed by main effects on the group variable. Hand dominance refers to effects that differentiate the dominant hand (most used) from the nondominant hand (less used). Dominance was not explicitly measured in participants, but for purposes of discussion, we adopted the commonly held view that the right hand is dominant in right-handers and the left hand is dominant in left-handers. According to our analyses, hand dominance effects tended to be revealed by Group × Hand interactions. In instances in which both groups produced similar results on a dependent variable, we interpreted those effects as reflecting variables not necessarily related to correlates of handedness or hand dominance.

With respect to average period and its *CV*, hand dominance appeared to be an influential factor. The average period was slightly shorter for the dominant than for the nondominant hand in both left-handers and right-handers. In addition, *CV* period was larger for the nondominant hand in both groups. A similar pattern of results was found for the aspect ratio. For both left- and right-handers, trajectories drawn by the dominant hand produced a higher average aspect ratio (indicating they were more circular) than trajectories drawn by the nondominant hand. In addition, aspect ratio *SD* was larger for the nondominant hand in both groups, indicating more variability in the circularity of the shapes. The *CV* radius also revealed a significant Group × Hand interaction, again indicating that the dominant hand was less variable than the nondominant hand.

A surprising finding relates to the within-hand variable of mean radius, which we used to assess effects on circle size. Recall that participants were not given specific instructions about circle size, other than to draw comfortably. Most interesting, circles drawn by the left hand tended to be larger on average than circles drawn by the right hand, in both left-handers and right-handers. That common finding across the two groups suggests that there possibly are basic neural correlates underlying the planning of circle size that might be independent of correlates of handedness or hand dominance.

Taking all within-hand factors into consideration, it appears that whereas average period and degree of ellipticity (aspect ratio) are determined to some extent by hand dominance, average circle size (radius) does not depend on hand dominance. All measures of variance appeared to be related to hand dominance effects, given that the nondominant hand produced a larger variance than the dominant hand on all within-hand measures.

In the remainder of this discussion, we focus on implications about our primary findings relating lead hand to coordination mode and movement direction. With respect to direction of movement in parallel tasks, both left-handers and right-handers demonstrated a marked relation between right hand lead and CW movements and between left hand lead and CCW movements. Those findings suggest that for parallel tasks, the dominant hand does not necessarily lead. Rather, direction of movement might be a better predictor of which hand leads. We can think of at least two hypotheses to account for those effects.

It might be possible to explain some aspects of those effects by biomechanical factors, although we know of no studies in which those issues have been examined with respect to continuous circle drawing. For example, if the abduction (outward from the body) phase of movement is the more powerful, we might expect the outward phase to be the prime determinant of circle drawing speed. If we then examined the outward phase of movements performed in each direction, we might find that angles at both the shoulder and elbow joints of the right arm allow the muscles to produce more torque during clockwise than during counterclockwise movements. Clockwise would thus be the more powerful direction for the right hand. The opposite might apply to the left hand. In a parallel bimanual task, we might expect the lead hand to be the one moving in its more powerful direction. According to that argument, the left hand would lead for counterclockwise parallel movements and the right hand would lead for clockwise parallel movements. In symmetrical bimanual tasks, both hands would be moving in their more powerful directions, so hand lead would be determined by other factors, such as correlates of handedness or arm strength.

An alternative account relates the natural directional tendencies of the hands to cerebral dominance in planning of directional properties. Given that participants started drawing at approximately the 12 o'clock position on the tablets, parallel clockwise movements required an initial rightward motion, and parallel counterclockwise movements required an initial leftward motion. It is possible that each hand is accustomed to lead when the initial direction of motion is toward its side. The cerebral hemisphere that governs the particular hand might therefore adopt what is akin to a directional preference. Consistent with the notion of a directional preference, lesions of the parietal lobe have been shown to produce deficits in directing covert attention in the direction opposite the lesion (e.g., Posner, Walker, Friedrich, & Rafal, 1987).

In a variant of the just-mentioned account, attentional processes are implicated. It is possible that with the instruction to move clockwise, attentional processes are directed rightward, and with the instruction to move counterclockwise, attentional processes are directed leftward. Because mirror symmetrical bimanual tasks would cancel out those opposing attentional vectors, phase lead effects would be close to zero with mirror symmetrical drawing. One can easily test that account by applying an overt attentional manipulation and examining patterns of phase lead in the two parallel modes. If attention is a strong determinant of lead hand, additional attention to the task of one hand should further increase its phase lead. Alternatively, if direction of motion is the strong determinant of phase lead, then extra attention should not further affect phase lead of the attended hand.

Because the earlier predictions were clear-cut and easily testable, we incorporated them in a follow-up experiment on a group of 8 right-handed participants. We used a within-participant design in which the variables attention to one task and direction of drawing were crossed. The four conditions were (a) attention to left hand task, clockwise parallel circles; (b) attention to left hand task, counterclockwise parallel circles; (c) attention to right hand task, clockwise parallel circles; and (d) attention to right hand task, counterclockwise parallel circles. We analyzed the effects by using repeated measures ANOVA on the same variables as in the primary experiment reported in this article.

The results of the control experiment were clear. There was a highly significant main effect of condition on mean phase, $F(3, 21) = 18.51$, $p < .001$. Post hoc comparisons revealed that the two clockwise drawing conditions were not significantly different from each other, nor were the two counterclockwise conditions significantly different from each other, (both $Fs < 1.0$). However, each of the clockwise conditions differed from each of the counterclockwise conditions (all $ps < .001$). Most important, the results indicated that visual attention to one hand or the other did not change the phase lead significantly in those parallel tasks. Movement direction appeared to be the primary determinant of phase lead effects in parallel tasks. Those results support the idea that the two cerebral hemispheres might be differentially equipped for processing motions in different directions.

Our present findings indicated that lead hand effects are similar in left-handers and right-handers with respect to parallel tasks. One classification of circle drawing tasks is that parallel drawing reflects allocentric spatial coordinates (Swinnen et al., 1997). One can conceptualize parallel trajectories as following a common point in external space, thus making the direction of movement identical for both hands (Swinnen et al., 1997). We recently recommended that that notion be extended to account for trajectories performed in the absence of vision by suggesting that the same basic mode of spatial planning is used even with imagined points in space (Franz, 2000a, 2000b). A recent study from our laboratory, based on findings in two groups of acallosal participants—people with callosotomy (also termed split-brain) and people with callosal agenesis—sheds some light on the influence of cerebral dominance. Callosotomy patients have undergone a surgical procedure whereby the corpus callosum has been severed so that the spread of epileptic seizures from one hemisphere to the other can be stopped. People with callosal agenesis were born without a corpus callosum. It was interesting that those two groups demonstrated opposite patterns of cerebral dominance on tests we applied as part of our normal protocols. Individuals with callosotomy were characterized as being left-hemisphere dominant, whereas the callosal agenesis group was characterized as being right-hemisphere dominant. The most interesting result from that study was a double dissociation between the two groups. The callosotomy group was unable to perform parallel circles, despite no difficulty with the mirror symmetrical conditions. In contrast, the callosal agenesis group was unable to perform mirror symmetrical circles, despite no difficulty with parallel circles (Franz, 2000a, 2000b; Franz, Rowse, & Finlay, 2001).

As described earlier, in addition to possible cerebral differences in directional planning, our recent findings suggest that the left hemisphere is dominant for organizing movements that are represented in egocentric space, whereas the right hemisphere is necessary for performance of parallel (allocentric) movements. Without a corpus callosum, the flexible control between those modes is lost (Franz, 2000a, 2000b). That view seems consistent with an earlier proposal by Watson and Kimura (1989), who also used a motor task. They reported in right-handers a superior right hand performance in throwing but not in intercepting a projectile. The latter task would rely on more external information than the former, suggesting cerebral differences in mode of processing.

With respect to the observed effects on mirror symmetrical tasks, one possible account for the predominant right hand lead in mirror symmetrical tasks of right-handers and the mixed hand lead in left-handers relates to issues of hand strength or biomechanics. It is possible that left-handers tend to have a more equilibrated system of bimanual control than right-handers. As a result, left-handers might tend to lead with the left and right hands more interchangeably when the tasks demand bilaterally symmetrical actions. That equilibration might relate to the relative strengths of the two hands (or arms), attentional properties, or technological circumstances. With respect to the latter possibility, people might be somewhat conditioned to using the right hand when they might naturally use the left to operate knobs and levers that are often positioned for right-handed people. It is also possible that a more equilibrated system of bimanual control might result from properties of callosal interactions that might differ between left-handers and right-handers, an issue that has not been resolved.

The finding that left-handers display mixed patterns of lead hand in mirror symmetrical drawing is additionally intriguing, given other research findings on the organization of speech processes. It has been suggested, for example, that speech is less lateralized in left-handers than in right-handers (Branch, Milner, & Rasmussen, 1964; Kimura, 1973; see also Knecht et al., 2000). Although pure speculation, it is tempting to raise the possibility that bimanual planning of mirror symmetrical movements might rely on an underlying representation that is also somewhat bilateral, as has been proposed for speech representation in left-handers. That possibility is certainly consistent with recent findings from other bimanual studies (Franz, Waldie, & Smith, 2000).

Finally, why do our findings on the relation of hand dominance and lead hand differ from those of other studies? As stated earlier, in previous studies, investigators have incorporated auditory pace signals or visual templates, or both, to guide movements. It might be the case that those requirements themselves influenced hand lead effects via attentional processes of some type or cerebral dominance factors. The focus in previous work was on phase relations, so it might have been optimal to control for both circle size and speed. In the present study, a different focus was adopted. Our aim was to examine both within-hand and between-hands variables with as few task constraints as possible to specifically focus on whether group differences occur between left-handers and right-handers. Accordingly, the findings from the present study were based on relaxed movement demands with no imposed visual or auditory information other than the requirement that the circles be drawn within the drawing surface of the digitizer tablets. Of note, all circles were drawn with a diameter that was substantially smaller than the 30-cm × 30-cm tablet surface size.

Some other considerations might be worthwhile to consider. First, it is possible that small sample sizes (particularly of left-handers) and different procedures for handedness assessment accounted for some differences across studies. We attempted to overcome such limitations by testing relatively large groups of both left-handers and right-handers, and the groups produced nearly nonoverlapping distributions on the handedness inventory. Related to that point is the number of trials collected in each condition. Indeed, because of variability across trials, this type of research poses some difficulty in attempting to increase the number of trials per condition while still avoiding fatigue effects. Reporting the standard error for dependent measures can sometimes be helpful in interpreting effects that are significant from those that are not, especially when small numbers of trials are used. It is possible that a lack of statistical power with small sample sizes or numbers of trials might lead to null effects when additional observations might have yielded differences, so those considerations are quite important. A third consideration relates to the averaging of positive and negative phase differences. Most notable, when averaged across trials, those values will cancel one another, resulting in a close to zero phase difference. In the present article, one case was demonstrated in which computing the absolute values of phase difference led to different conclusions than the average of the signed values. We would not have known that had we not considered the values on an individual trial basis.

In summary, the claim that the dominant hand leads in bimanual circle drawing was not supported by our findings. With respect to mirror symmetrical circle drawing, it tends to be the case that the dominant hand leads in right-handers and less so in left-handers. Because different patterns of results were observed in the two groups, we cannot rule out the possibility that handedness plays some role in determining lead hand in mirror symmetrical tasks. With respect to parallel circle tasks, right-handers and left-handers produced virtually identical patterns of results. The right hand tended to lead when movements were in the clockwise direction, and the left hand tended to lead when movements were in the counterclockwise direction. It appears that for parallel tasks, handedness does not determine lead hand.

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APPENDIX

Algorithm for Trajectory Variables

The use of kinematic landmarks (such as compass points) is a robust and reliable method for trajectory analysis. The analysis developed in this article was built on kinematic methods in which continuous phase is computed across trajectories that might not form perfect circles or revolve around a stable center.

We developed the following algorithm to build upon the robustness of kinematic analysis and to make it more flexible by individually associating each point on a trajectory with a figure that subtends exactly 360°.

Step 1

Using two extremes of a nine-point moving window, we calculated as follows the tangential angle (*TA*, also referred to as *bearing*) for each point (n), with respect to 12 o'clock. A definition follows each equation:

$x\text{dif}_n = x_{n+4} - x_{n-4}$, (Displacement difference along x-axis)

$y\text{dif}_n = y_{n+4} - y_{n-4}$, (Displacement difference along y-axis)

and

$\text{TA}_n = \arctan x\text{dif}_n/y\text{dif}_n$.

Step 2

To calculate instantaneous values for whole-circle variables such as period and eccentricity, we associated each point on the trajectory with a single circle. For each point (n), the algorithm searches backward along the *TA* profile until it finds a start point s_n at which the *TA* is 180° different from the *TA* at n. The algorithm then searches 180° forward to find an endpoint (e_n). The points in between s_n and e_n approximate a circle. One calculates the period for that circle by taking the time difference between s_n and e_n, and one derives the coordinates describing the circle's center by measuring the circle's upper and lower extremes in the x- and y-axes and then taking values halfway between. One calculates the radius at n by measuring the length of a line drawn from the circle center to n, and n's angle of displacement by measuring the orientation of that line with respect to 12 o'clock. The following equations were applied:

$\text{Period}_n = \text{time}_{en} - \text{time}_{sn}$. (Period of the circle)

$\text{Range} = s_n$ to e_n, where range is the set of all points describing the circle.

$\text{Center}.x_n = \text{midpoint}[\min(x_{\text{range}}), \max(x_{\text{range}})]$. ($x$ coordinate of the circle's center)

$\text{Center}.y_n = \text{midpoint}[\min(y_{\text{range}}), \max(y_{\text{range}})]$. ($y$ coordinate of the circle's center)

$\text{Radius}_n = [(x_n - \text{center}.x_n)^2 + (y_n - \text{center}.y_n)^2]^{1/2}$. (Radius)

$\text{Angle}_n = \arctan[(x_n - \text{center}.x_n)/(y_n - \text{center}.y_n)]$. (Angle of displacement)

Step 3

With the algorithm, one calculates phase difference at each point in time by measuring the difference between the angles of displacement of the left and right hands. Note that that measure is the phase difference as an angle, whereas in previous studies phase difference has often been reported as time. In the algorithm, by dividing angular phase by 360° and then multiplying it by the instantaneous period, one converts angular phase difference into temporal phase difference. If the instantaneous period of the left hand is different from that of the right hand, an average is used. Those procedures are denoted by the following equations:

$\text{Phasedif}_n = \text{angle}_n(\text{left}) - \text{angle}_n(\text{right})$ (Angular phase difference)

$m\_\text{period}_n = \text{mean}[\text{period}_n(\text{left, right})]$. (Period, averaged between hands)

$t\_\text{phasedif}_n = \text{phasedif}_n/360° * m\_\text{period}_n$. (Temporal phase difference)

Step 4

Circular hand motions are very often elliptical, so the majority of the circles used to calculate the above variables will actually be ellipses. In order to calculate aspect ratio, the algorithm rotates every point's associated circle through 180° in 5° steps, measuring the vertical diameter at every step. The algorithm selects the largest value as the major diameter, and the orthogonal value as the minor diameter. One derives aspect ratio by dividing the minor diameter by the major diameter. We have provided in the text another popularly used measure of how circular or elliptical a figure is, termed *eccentricity*, to aid in comparisons with other research. The following equations were used:

$\text{Rot}\_y_n(\theta) = \cos(\text{angle}_n + \theta) * \text{radius}_n$. (Coordinate of n, after being rotated $\theta°$)

$\text{Range} = s_n$ to e_n. (Range all points along circle n)

$\text{Diam}_n(\theta) = \max[\text{rot}\_y_{\text{range}}(\theta)] - \min[\text{rot}\_y_{\text{range}}(\theta)]$. (Vertical diameter of circle n, after being rotated $\theta°$)

$\text{Maj\_diam}_n = \max[\text{diam}_n(0 \text{ to } 180°)]$. (Major diameter of circle n)

$\text{Min\_diam}_n = \text{diam}_n(\theta_{\text{maj\_diam}} + 90°)$. (Minor diameter of circle n)

$\text{Eccen}_n = (1 - \text{aspect\_ratio}_n{}^2)^{1/2}$. (Eccentricity)

Step 5

For a perfect circle, any two points with the same TA would also have the same angle of displacement, but hand-drawn trajectories tend not to be perfect circles. They are more often a succession of rough ellipses with an unstable center. That means that for many points, the range calculated from the TA profile will subtend slightly more or less than 360° of displacement. For that reason, the range calculated in Step 2 is not a reliable measure, which means that all other measures that involve the range are also not reliable. The algorithm uses multiple passes to solve that problem. On the first pass, the range is derived from the tangential angle data calculated in Step 1, by searching180° forward and backward from each point. On the second pass, the algorithm recalculates the range, deriving it from the angle of displacement data calculated in the first pass. On the third pass, the angle of displacement data calculated in the second pass is used, and so on. By using that multipass process, we found that the range values converged, and there was usually no further convergence observed after the sixth pass. We therefore used the range values from the sixth pass to generate the final values.

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