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Attentional Distribution of Task Parameters to the Two Hands During Bimanual Performance of Right- and Left-Handers

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ABSTRACT. The author tested 12 left-handers and 12 right-handers on a bimanual circling task to examine how attention (either visual or nonvisual) to the task of 1 hand affects within-hand task parameters and whether the effects of attention manipulations are similar in left- and right-handers. The novel prediction that the attended task would be produced larger than the unattended task was confirmed in both handedness groups. The magnitude of the effect on circle size was more pronounced under visual than under nonvisual attention manipulations. The primary effects of attention were similar in the 2 handedness groups, although left-handers demonstrated some evidence of stronger parameter coupling between hands than right-handers did.

Key words: attention, bimanual, handedness

In a recent study, Franz, Rowse, and Ballantine (2002) examined whether the dominant hand always leads the nondominant hand in a bimanual task by investigating parameters of bimanual circle drawing in left- and right-handers. The answer to that question was twofold. Yes, the dominant hand tends to lead when circles are drawn in a mirror-symmetrical mode with respect to the body midline. In contrast, the direction of movements appears to be a better predictor of hand lead than hand dominance when the movements are performed in a parallel mode in which the hands move in the same direction in external space. My colleagues and I interpreted the former finding as converging support for a role of hand dominance in leading a bimanual task (Amazeen, Amazeen, Treffner, & Turvey, 1997; Carson, Thomas, Summers, Walters, & Semjen, 1997; Semjen, Summers & Cattaert, 1995; Stucchi & Viviani, 1993; Swinnen, Jardin, & Meulenbroek, 1996; Treffner & Turvey, 1996) and the latter as evidence of lateralized directional planning (Franz, 2000a, 2000b; Franz et al., 2002). A third, albeit serendipitous, finding emerged in the metrical aspects of the spatial form of the trajectories. Circles produced by the left hand tended to be larger than those produced by the right hand, despite tightly coordinated drawing between the hands. The consistency of that finding across right- and left-handers led us to speculate that production of circle size depends on neural processes that do not seem to be correlates of handedness or hand use. Nor can the finding be easily interpreted as reflecting purely execution parameters such as higher force levels, speed of movement, or muscle mass, given that it was the left hand in both groups that produced larger circles.

In the present study, I sought to examine whether attention might be one mediating variable on the size of circles produced bimanually. Specifically, could an asymmetry of attention to tasks of the two hands result in different sized circles despite a tight coordination between the hands? A number of influential studies have provided support for the view that constraints on attention result in forms of task interference when distinct tasks are performed concurrently by the two hands. For example, in earlier studies from at least two different laboratories, the production of two nonharmonic timing patterns was found to result in large errors in bimanual performance (Klapp, 1979), and those errors tended to increase with the frequency demands of the movements (Peters, 1981, 1985). Further analysis based on the patterns of errors revealed that it was more difficult for right-handed participants to tap as fast as possible with the left hand while following an established pace with the right than to perform the reverse hand–task assignment (Peters, 1981, 1985). Peters interpreted those findings as evidence of an asymmetry of attention to the two hands during

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bimanual performance. His assertion was that tapping in pace to a metronome is relatively automatic, whereas tapping freely as fast as possible demands sustained attention. Accordingly, the left hand tends to suffer when its task requires sustained attention that is normally devoted to the right-hand task. Guiard (1989) demonstrated evidence of asymmetries in attention in skilled pianists attempting to combine a voiced task and a bimanual keyboarding task. The musicians were better able to sing the right-hand part of the music while keying the left-hand notes, than to sing the left-hand part while keying the right-hand notes.

In other studies, selective attention manipulations to the tasks of one or both hands have been used under otherwise identical individual task requirements. The primary focus in those studies has been on the coordination dynamics, or the patterns of phase relations between the hands. Investigations have been conducted on the effect of attention on coordination dynamics in bimanual tasks that include drawing (Swinnen et al., 1996; Wuyts, Summers, Carson, Byblow, & Semjen, 1996), pendula swinging (Amazeen et al., 1997), and joystick movements (Temprado, Zanone, Monno, & Laurent, 2001). Using very different methods, investigators have accumulated evidence in support of the finding that a dominant-hand phase lead tends to increase with attention to the lead hand (Amazeen et al., 1997; Swinnen et al., 1996). The effects of attention on within-hand spatial properties are less well, if at all, understood, albeit some incidental findings have been reported. For example, Wuyts et al. (1996) were interested primarily in whether selective visual attention to the nondominant hand during bimanual circling at different frequencies would influence the coordination dynamics. Although their data failed to provide support for that intriguing possibility, some unexpected within-hand effects emerged. Attention to the nondominant hand resulted in better spatial accuracy of the task performed by that hand as compared with conditions of no attention to that hand. The enhancement of spatial accuracy occurred at the expense of accuracy of the task performed by the dominant hand.

Swinnen et al. (1996) examined performance of left- and right-handers on circle tracing with both hands together under conditions of free vision, visual monitoring of the dominant or nondominant hand, or blindfolded. They were also interested primarily in whether and how direct visual attention (which they called *monitoring*) would affect bimanual coordination dynamics. They observed that phase differences were largest with visual monitoring of the dominant hand, smallest with visual monitoring of the nondominant hand, and of intermediate magnitude in free-vision and blindfolded conditions. In addition, Swinnen et al. reported the somewhat incidental finding that circle diameter was largest with visual monitoring of the dominant hand. Swinnen et al. (1996) and Wuyts et al. (1996) reached very different conclusions, most likely because of the different methods used in their studies. Moreover, stimuli such as pacing tones and visual templates were used in both studies, and one could argue that the use of those stimuli itself might have influenced attention processes in ways that are not fully understood.

To my knowledge, there has been no in-depth task analysis of the effects of attention to the task of each hand during bimanual performance that was uninfluenced by extraneous stimuli such as pacing tones or visual templates. One can answer some important theoretical questions by conducting such an investigation. The first concerns the way in which attention is allocated to the two hands when the tasks are well within the capabilities of the performer. How is attention apportioned to the two hands in the pure and simple case of bimanual actions, and do left- and right-handers show similar patterns of results? Answers to those questions should offer an understanding of how the neural system naturally apportions attention between the hands during concurrent actions, a question that remains novel in the context of existing research. Second, are all forms of attention created equal? That is, can researchers consider findings based on the application of selective visual attention to one hand's task or to the other's as being representative of how attention operates? Although in past studies only selective visual attention has been manipulated, we can also use the novel manipulation of a form of covert attention, which is referred to herein as *nonvisual*. Suppose a person is asked to close his or her eyes when performing the bimanual task but to concentrate on one or the other hand's task. Do the effects of that nonvisual form of attention on task parameters parallel the effects of visual attention? Thus, an additional novel aspect of the present study was the incorporation of manipulations of visual and nonvisual attention. I hypothesized that visually attended circles would be larger than visually unattended circles. Of primary empirical interest was whether nonvisual attention would produce effects similar to those of visual attention.

In this experiment, nonvisual attention and direct visual attention to each task were separately manipulated during bimanual circling. Participants were instructed to draw bimanual circles at their own preferred pace and circle size. My purpose in using those relaxed demands was to impose as few experimental constraints as possible so that direct observations of the effects of attention could be measured with a minimal influence of other possible confounding variables. Participants were instructed in some conditions to visually attend to the task of one hand while the other hand was hidden from view (visual attention conditions). In other conditions, they were instructed to attend to the task of one hand by concentrating, with eyes closed (nonvisual attention conditions).

Method

Participants

Groups of 12 right-handed participants and 12 left-handed participants were tested; equal numbers of men and women were in each handedness group. All participants were recruited from the University of Otago Psychology

Department participant pool. Right-handed participants ranged in age from 20 to 39 years (M = 24.10 years, SD = 5.17). The mean score on the handedness inventory (Oldfield, 1971) across the right-handed group was .78 (SD = .15), on a range of –1 (*strongly left-handed*) to +1 (*strongly right-handed*). The left-handed participants ranged in age from 18 to 48 years (M = 26.2 years, SD = 8.8). The mean score on the handedness inventory for the left-handed participants was –.67 (SD = .27).

Apparatus

The experiment was conducted in an enclosed soundproof experimental booth. The inner wall of the booth was lined with black curtains so that visual distraction was prevented. Participants were seated, with the center of the body directly in line with the division between the two Kurta XGT digitizer tablets (each 30 × 30 cm) that were placed side by side on a table. To draw, they used magnetic pens that did not leave a visible trace. A standard computer sampled the x and y positions of the pen tips 100 times per second, with a spatial accuracy of .0025 cm.

A specially constructed box was placed directly over one tablet so that one of the participant's hands was hidden from view. The wooden box was 46 cm long, 44 cm wide, and 27 cm high. The box had an open end so that participants were able to insert one hand. The open end had a curtain rod with a black silk curtain that could be opened or closed so that the hand could be seen or obstructed from view. A black cape extending from the box was fastened to the back of the participant's shoulder so that no peripheral vision of the hidden arm was possible. The box could be placed over the right or left hand so that the arm could be obstructed from the participant's view without disturbing any movement. The box was used both for visual and nonvisual attention conditions, although participants performed the nonvisual conditions with eyes closed.

Design

The experiment was a repeated measures mixed-effects design in which handedness group was used as a between-participants variable (left- vs. right-handed). All participants within each group performed in the following four conditions: nonvisual attention to the left-hand task (with eyes closed), nonvisual attention to the right-hand task (with eyes closed), visual attention to the left-hand task (with right hand and arm blocked from view), and visual attention to the right-hand task (with left hand and arm blocked from view). The conditions were counterbalanced, and no 2 participants within a group performed them in the same order. The abbreviations Non, Vis, L, and R, which are used throughout this article, represent nonvisual attention, visual attention, left-hand task, and right-hand task, respectively.

Procedure

I first calibrated and tested the tablets to ensure that both were recording accurately. Verbal instructions describing each experimental condition were then given. In nonvisual attention conditions, participants were instructed to close both eyes and concentrate on the task of one hand. In visual attention conditions, participants were instructed to watch the task of one hand while the other hand was blocked from view. In neither condition were they instructed to focus on any specific property of the task. Participants were instructed to begin each trial from approximately the top (12:00 o'clock) positions of the drawing tablets and to draw circles with an initial inward direction (i.e., clockwise with the left hand and counterclockwise with the right). Participants were instructed to choose a comfortable circle size and speed. Those instructions were the only experimental constraints imposed on the circle-drawing motor task; they were imposed so that all participants would adopt a similar drawing mode. Before the actual test, I gave participants approximately 30 s of practice with their eyes open in order to determine the most comfortable drawing parameters. They were then asked to maintain those comfortable parameters for all conditions. Just before each performance block, the experimenter verbally indicated and tapped the hand of the to-be-attended task.

Following a repeat of the instructions for the first condition, testing of the first trial began. The experimenter said "ready, go" to begin each trial, and the computer began sampling after movement commenced. After the 8-s continuous trial, the experimenter gave a verbal "stop" command. Eight trials per condition were collected, with the first two considered as practice. I allowed participants to rest between trials to reduce any effect of fatigue; during that time, the experimenter changed the box and cape extension from one tablet (and arm) to the other, depending on the upcoming condition. That procedure was continued until all four conditions were tested. On conclusion of the experiment, participants were asked to fill out the handedness questionnaire and to answer some general questions about their performance, and they were fully debriefed. With rest between trials, each testing session lasted approximately 40 min.

An experimenter was present in the testing booth during all data collection. That person operated the computer and monitored the participant to make sure there were no violations of instructions. The experimenter also made certain that the participant remained in a stable posture during the entire time of testing and that he or she watched the task of one hand when so instructed.

Data Treatment

The primary within-hand variables of interest were circle radius, period, and aspect ratio, all traditional measures used to assess spatial and temporal parameters of bimanual circling.[1] I computed all variables by using in-house algorithms. To best capture the variables of interest, I calculated continuous phase across the trajectories as an initial step, given that the trajectories might not form perfect circles and that they might not revolve around a stable center. Tangential angle (TA), also known as *bearing*, was there-

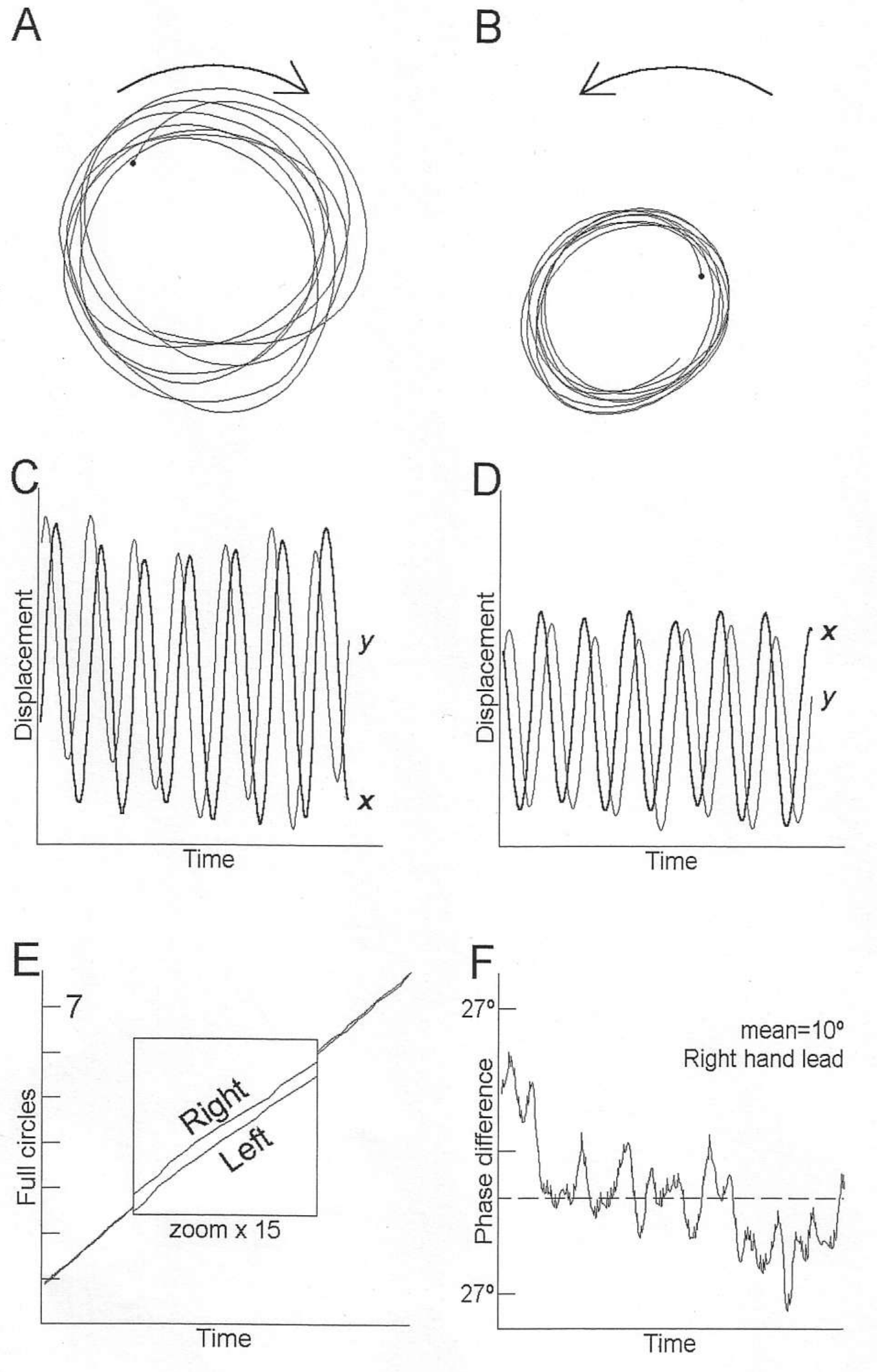

FIGURE 1. Representative plots are shown for one trial from a right-handed participant in the VisL (visual attention to the task of the left hand) condition. Displacement (cm) in x versus y is shown for 6 s of the trial for the left- (**A**) and right- (**B**) hand tasks. For the left- (**C**) and the right-hand (**D**) tasks, displacement versus time is also shown. (**E**) Cumulative displacement in angular degrees across time is depicted for the movements of both hands, followed by (**F**) instantaneous phase differences between hands in angular degrees across time. The integrated phase difference hovered around zero but showed a slight negative value on average, indicating a right-hand lead.

fore calculated for each point on the trajectory. I calculated a virtual circle for each point on the trajectory by searching backward 180° and forward 180° along the TA profile to approximate a circle of 360°. I then used each virtual circle to calculate instantaneous values of period, radius, and aspect ratio for its associated point. Complete details of the algorithm have been recently published elsewhere (Franz et al., 2002). In the interest of space, an abbreviated description of the computations for each variable is given next.

Within-hand variables were calculated on the basis of the following procedures. For each virtual circle, period was calculated as the time between start and end points. To calculate the radius, the circle center was defined as the midpoint of the *x* and *y* values bounded by the virtual circle. The radius was calculated as the distance between the reference point of each virtual circle and the circle center. Finally, an aspect ratio was computed to approximate degree of circularity. For each circle, I first calculated the major axis displacement by measuring the diameter of the virtual circle at 5° steps and searching for the maximum. The minor diameter was defined as the distance of the axis orthogonal to the major diameter. Aspect ratio was calculated as the minor diameter divided by the major diameter. A perfect circle would produce an aspect ratio of 1.00, whereas a perfect line would result in an aspect ratio of zero (Franz, Zelaznik, & McCabe, 1991).

An angle of displacement was calculated for each hand's movement, to be used in subsequent calculations of phase difference. Angle of displacement refers to the orientation of a line drawn from the circle center to a point on the trajectory. The angle of displacement is defined in degrees, using (12:00 o'clock) as a reference. To compute a measure of phase, I calculated the difference between the angles of displacement of the left and right hands. For example, if at some point in time the left hand was at a 45° orientation and the right hand was at 30°, the phase difference would be a left-hand lead of 15°.

Using the procedures just outlined, I calculated a mean for each within-hand measure (radius, cycle period, and aspect ratio) and each between-hand measure of phase across all points within each trial. A corresponding measure of variance was also computed for each variable. Because variance in radius tends to vary with the mean, I computed the coefficient of variance (*CV*) as a measure of variance in radii by dividing the standard deviation (*SD*) by the mean (*M*).

In addition to the algorithm just outlined, our earlier algorithms based on peak values of kinematic landmarks were applied to those data (e.g., Franz, 1997; Franz & Ramachandran, 1998). Similar patterns of results (and nearly identical values on some variables) were obtained across the two types of algorithms. Therefore, the analyses derived from the algorithm just outlined are the only ones reported.

For each within-hand variable (mean radius, mean period, and mean aspect ratio, and a measure of variance of each), I applied a repeated measures mixed-design analysis of variance (ANOVA) by using the within-participants variables condition (4), hand of task, referring to left or right (2), and trial (6), and the between-participants variable group (left- and right-handers). The primary between-hand variable was phase difference. Signed phase difference between the hands was computed for all points within each trial. Because those values could be positive (indicating left-hand lead) or negative (indicating right-hand lead), averaging of the values could cancel any apparent hand-lead effects. Therefore, to preserve the magnitude of phase, I also computed a measure of absolute phase on each trial. Thus, for between-hand variables (mean signed phase difference, absolute phase difference, and *SD* phase difference), repeated measures ANOVAs on the within-participants variables condition (4) and trial (6) and the between-participants variable group (2) were applied. Planned contrasts between each condition were performed on mean radius, given that there were specific a priori predictions for that variable. I applied post hoc Newman–Keuls tests, where appropriate, to further disentangle significant main effects.

Results on radius, period, aspect ratio, and phase are described for each Results section in that order. Statistically significant results to an alpha level of $p < .05$ are described unless specified otherwise. Although the focus in the Results and Discussion is on circle size (radius measures), a brief description of results for other within-hand and between-hand variables is provided so that circle size effects can be interpreted within a context.

Results

Figure 1 depicts a trial in which the participant was instructed to visually attend to the task of the left hand. As can be seen from the figure, the hands moved reasonably smoothly in a mirror symmetrical mode, and the trajectories were approximately circular. The *x* versus *y* displacement plots (upper panels) reveal a larger circle size for the attended left-hand task (Panel A) compared with that for the unattended right-hand task (Panel B). Those differences are also apparent in the displacement versus time profiles, revealing larger magnitudes of displacement in both dimensions of the attended task (Panel C) compared with those of the unattended task (Panel D). The phase difference between hands across cycles of movement was close to zero (Panel E), with an instantaneous phase difference whose average across time was a negative value, indicating a right-hand lead on average (Panel F). The phase lead in degrees is shown. Although that trial was randomly selected, not all trials of that type revealed such large differences in size between the two hands. However, one should take into consideration the small drift in the trajectories of the left-hand task of Figure 1, which makes the overall picture look larger than any individual circle cycle. As described earlier, our algorithm for computing circle size and other variables has a built-in mechanism for dealing with an unstable circle center.

Radius

The grand mean radius was 5.015 cm ($SE = 0.361$). Mean radius and CV for each condition are shown in Table 1. A significant main effect of condition was found on mean radius, $F(3, 66) = 9.06$, $p < .001$. As can be seen from the values in Table 1, the VisL condition resulted in a significantly larger mean radius than did any other condition, as revealed by post hoc comparisons. The nonsignificance of the Condition × Group interaction revealed that those effects were not reliably different for left- and right-handers, $F < 1.00$. Moreover, there were no reliable differences in the overall mean radius for left- and right-handers, $F(1, 22) < 1.00$.

As hypothesized, there was a highly significant Condition × Hand interaction on mean radius, $F(3, 66) = 10.02$, $p < .001$. That can be clearly seen in Figure 2, which shows that the attended hand always produced a larger circle radius, on average, than the unattended hand did, under both visual and nonvisual conditions. The Condition × Hand interaction was further examined on the basis of difference scores between the attended and unattended hands in each condition. Subtracting the mean radius for the unattended hand from the mean radius of the attended hand on a participant-by-participant basis in each condition revealed approximations of the average difference scores. Planned contrasts revealed that both visual attention conditions, VisL and VisR, produced significantly larger difference scores than did their corresponding nonvisual attention conditions, NonL and NonR. No other significant effects were

TABLE 1. Mean Period, Radius, Aspect Ratio, and Signed Phase Difference, Averaged Across Left- and Right-Handers for Each Condition

	Period (ms)		Radius (cm)		Aspect ratio		Phase difference	
Condition	*M*	*SD*	*M*	*CV*	*M*	*SD*	*M*	*SD*
NonR	1,135	41	4.9	.081	.82	.01	−3.4°	10.2°
NonL	1,143	43	4.8	.082	.83	.01	−1.4°	10.0°
VisR	1,078	42	5.0	.082	.83	.01	−9.3°	10.5°
VisL	1,081	40	5.4	.084	.85	.01	2.7°	10.4°

Note. Negative values of phase indicate a right-hand lead, and positive values indicate a left-hand lead. NonR and NonL = attention to the right and left, respectively, in the nonvisual condition; CV = coefficient of variation; VisR and VisL = attention to the right and left, respectively, in the visual condition.

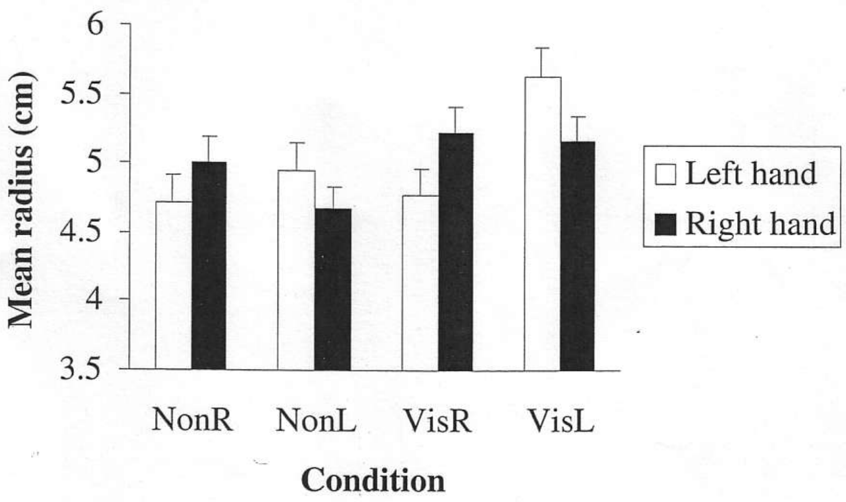

FIGURE 2. Mean radius (cm) and standard error (SE) for the left- and right-hand tasks are shown for the four conditions. Given that there were no significant differences between handedness groups, the data were averaged across left-handers and right-handers. Non and Vis = nonvisual and visual attention, respectively. L and R refer to the hand attended to, left or right, respectively.

revealed from comparisons of difference scores (all *ps* > .05). The three-way interaction between hand of task, condition, and group was not significant, which revealed similar patterns of results in left- and right-handers, $F(3, 66) = 1.73$, $p = .169$.

Together, those results indicate that the effects on circle size occurred with visual attention or nonvisual attention to one task, although the magnitude of the difference in size between tasks was larger with visual attention. In addition, the VisL condition produced a larger overall circle size than did the remaining conditions (collapsed across the two hands). The effects were similar for left- and right-handers.

The values of *CV* radius for the four conditions can be seen in Table 1. A significant main effect of condition was observed, $F(3, 66) = 3.64$, $p = .017$; it was caused by a slightly larger *CV* radius in the VisL condition compared with that in either the NonR or NonL condition.

For *CV* radius, a significant Hand of Task × Group interaction revealed that a larger *CV* radius was produced by the nondominant hand of each group than by the dominant hand, $F(1, 22) = 6.24$, $p = .02$. In addition, a highly significant Condition × Hand of Task interaction on *CV* radius revealed a pattern similar to that obtained for mean radius, $F(3, 66) = 27.43$, $p < .001$. In both groups, the *CV* radius of the attended task was smaller, on average, than the *CV* radius of the unattended task.

In sum, the primary effect of importance was that the attended task was characterized by larger circles than was the unattended task; that finding confirmed the predictions of this experiment and demonstrated that the effect also applied to conditions of nonvisual attention. An additional novel finding was that the magnitude of difference in mean radius between tasks was larger under visual than under nonvisual attention conditions. The largest overall effects on circle size occurred in the VisL condition. In addition, circle radii were less variable for the attended than for the unattended task, and circle radii were more variable for the nondominant hand than for the dominant hand.

Period

The grand mean period across all conditions was 1,109 ms ($SE = 58.9$). Table 1 contains the mean and standard deviation for each condition. The main effect of condition was statistically significant, $F(3, 66) = 4.56$, $p = .006$. As revealed by the values in Table 1, the nonvisual attention conditions produced longer average periods overall than did the visual attention conditions. However, the two nonvisual attention conditions were not significantly different from one another, and the two visual attention conditions also were not significantly different from one another (both *ps* > .05). The Condition × Group interaction was not significant, indicating that the pattern of results of left-handers was not reliably different from that of right-handers, $F(3, 66) = 1.608$, $p = .196$.

Mean period was not significantly different for tasks of the two hands, on average, $F(1, 22) = 2.720$, $p = .11$. However, hand of task interacted significantly with group, $F(1, 22) = 14.52$, $p = .001$. The pattern of that interaction revealed that for left-handers, the right hand produced a slightly longer period than the left one did, and the pattern was just the opposite for right-handers. The magnitude of difference between the left and right hands amounted to only 3 ms for left-handers and 6 ms for right-handers, however, suggesting that those differences were actually quite small.

The grand mean of the *SD* period was 42 ms ($SE = 3$). The values of *SD* duration appear in Table 1. As can be seen from those values, *SD* period did not differ significantly across the four conditions; moreover, the Condition × Group interaction was not significant, both *F*s < 1.00. Consistent with the findings on mean period, there was a significant Hand of Task × Group interaction on *SD* period, $F(1, 22) = 6.14$, $p = .021$. That interaction revealed a slightly larger *SD* period for the right compared with the left hand in left-handers, and the opposite effect in right-handers. Thus, on average, the nondominant hand tended to produce more variance in period than the dominant hand did.

In sum, there was a longer average period in nonvisual than in visual attention conditions, and the dominant hand produced a shorter period than the nondominant hand did. That finding was accompanied by a larger variance for the nondominant than for the dominant hand task. A significant effect that differentiated left- and right-handers was the magnitude of difference between hands.

Aspect Ratio

The grand mean aspect ratio was .832 ($SE = .007$), revealing a slight deviation from circularity, on average. Most notable, there was no circle template, so some deviation from perfect circularity was expected. The values of mean and *SD* aspect ratio for each condition appear in Table 1. There was a significant main effect of condition on mean aspect ratio, $F(3, 66) = 3.233$, $p = .028$. As shown in Table 1, the values that made up that main effect differed only slightly in actual magnitude. Condition did not interact significantly with group, ($F < 1.0$). Moreover, hand of task just reached statistical significance, with the right hand producing a larger aspect ratio overall than did the left hand (.85 vs. .82), $F(1, 22) = 4.436$, $p = .047$. However, a significant interaction with group indicated that the left-hand aspect ratio was approximately the same as the right-hand aspect ratio in left-handers (both approximately .84), whereas the right-hand aspect ratio was substantially larger than the left-hand aspect ratio in right-handers (.86 vs. .80), $F(1, 22) = 6.136$, $p = .021$. Those results suggest that the between-hand coupling in shape was stronger in left-handers than in right-handers.

Of primary importance to the issues of investigation, the Condition × Hand of Task interaction was highly significant, $F(3, 66) = 37.28$, $p < .001$. The values of that interaction appear in Figure 3, which shows that in all conditions except NonL, the attended task had a larger average aspect ratio than did the unattended task. Those observations were

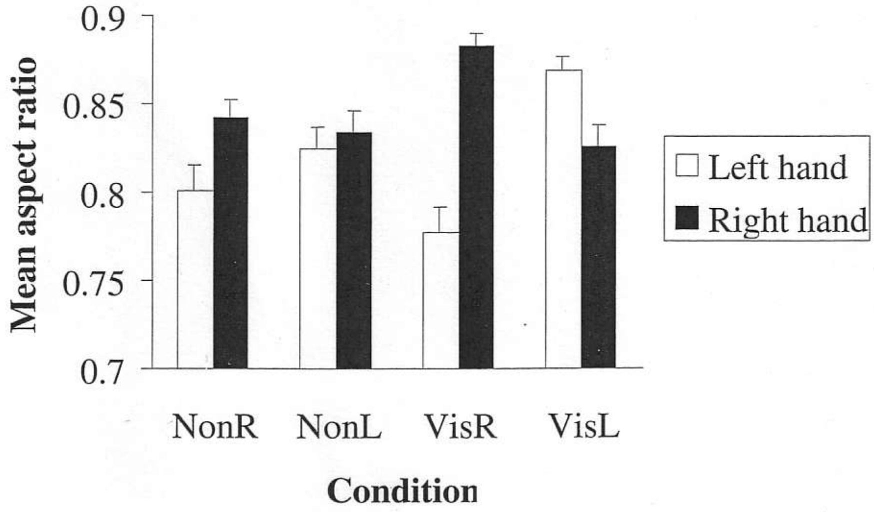

FIGURE 3. Mean aspect ratio (columns) and standard error (bars) for the left- and right-hand tasks are shown for the four conditions, averaged across left- and right-handers. Non and Vis = nonvisual and visual attention, respectively. L and R refer to the hand attended to, left or right, respectively.

statistically reliable, with significant between-hand differences in aspect ratio for all conditions except the NonL. The three-way interaction of Hand of Task × Condition × Group was not significant ($p > .05$).

In sum, mean aspect ratio was larger (closer approximation to circularity) for the attended than for to the unattended task. The only exception to that basic pattern occurred with nonvisual attention to the left-hand task. Those findings are consistent with the possibility that the left-hand task normally receives nonvisual attention and that the instruction to apply nonvisual attention to that task does not further alter spatial coupling in the bimanual task (with respect to task shape). The finding that the effects on task shape singled out the NonL condition from all others but effects on circle size did not might suggest that the underlying properties of parameterizing circle shape and circle size are distinct. With respect to *SD* aspect ratio, the only significant effect was a Group × Hand of Task interaction that revealed a larger average *SD* for the nondominant than for the dominant hand ($p < .001$).

Signed and Absolute Phase Differences

To ensure that the present procedures produced results on phase difference that were consistent with previous studies, I performed both signed and absolute phase analyses. In the interest of space, only the primary effects are reported. A thorough rationale for computing absolute phase appears in an earlier article (Franz et al., 2002). The grand mean phase difference between hands was –2.87° (SE = 1.47), with the negative sign indicating a right-hand lead, on average. The mean phase for each condition can be seen in Table 1. As can be seen from those values, the VisL condition was the only one that resulted in a left-hand lead, on average. The main effect of condition on mean phase was significant, $F(3, 66) = 6.211$, $p = .001$. The main effect was caused primarily by the large right-hand lead observed with visual attention to the right-hand task (see Table 1). That condition differed significantly from all other conditions in post hoc tests.

The above results indicated that the largest right-hand phase lead occurred with visual attention to the right hand. A main effect of group indicated, however, that left-handers produced a slight left-hand lead, on average (M = 2.81°) whereas right-handers produced an even larger right-hand lead, on average (M = –8.55°). In addition, condition interacted significantly with group, $F(3, 66) = 3.89$, $p = .013$. Figure 4 depicts the means and standard errors of that interaction. As can be seen in the figure, visual attention to the left-hand task resulted in a large left-hand lead in left-handers, whereas visual attention to the right-hand task resulted in a large right-hand lead in right-handers. Together, those results indicate that visual attention to the task of the dominant hand dramatically increased the phase lead of that hand relative to the nondominant hand in both left-handers and right-handers, consistent with research previously reported (see introductory comments).

The effects on absolute phase were straightforward. First, the grand mean was 11.15° (SE = 1.04), indicating that the magnitude of phase lead was quite a bit larger than were the signed phase values. Condition produced the only significant main effect, $F(3, 66) = 4.371$, $p = .007$. The absolute magnitude of phase difference was 7.80° in the NonR condition and 9.50° in the NonL condition, and those values did not differ reliably from one another. The absolute magnitude of phase difference was 12.40° in the VisR condition

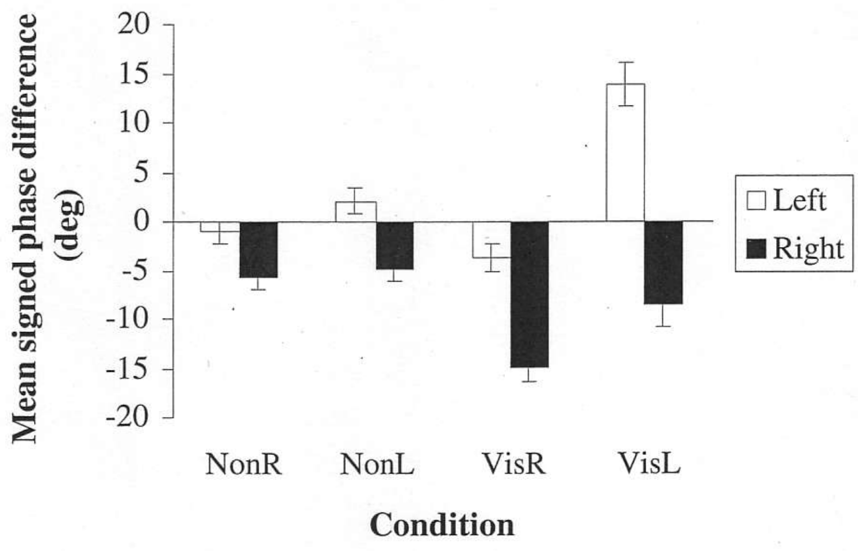

FIGURE 4. Mean signed phase difference (in degrees) and standard errors (bars) for each of the four conditions are shown for left- and right-handers. Non and Vis = nonvisual and visual attention, respectively. L and R refer to the hand attended to, left or right, respectively.

and 14.70° in the VisL condition, and those values also did not differ significantly from one another. However, both nonvisual attention conditions differed from both visual attention conditions in post hoc tests.

In sum, as expected, the dominant hand of each group tended to lead, and the nondominant hand tended to lag, consistent with other research on in-phase symmetrical bimanual tasks described earlier. In addition, visual attention to the dominant hand increased the phase lead of that hand relative to the unattended hand, also corroborating other research on the influence of attention on coordination dynamics (see introductory comments). It is also clear from those analyses that signed phase differences did not result from one hand's consistent lead of the other. In fact, there was evidence of a mixed hand lead in both groups whereby one hand led on some trials and the other hand led on the remaining trials. The mixed hand lead was particularly apparent in left-handers in nonvisual attention conditions; there was an approximately equal number of right-hand lead trials as left-hand lead trials (revealed by a counting analysis) in those conditions. The effect was much less apparent in right-handers, in whom the majority of trials were produced with a right-hand lead. Analyses on absolute phase revealed the interesting effect that the magnitude of phase difference was larger, on average, with visual than with nonvisual attention.

Discussion

My primary aim in this experiment was to perform an in-depth task analysis of the effects of visual or nonvisual attention on properties of bimanual circling, with a specific focus on circle size. A corollary aim was to examine whether effects of attention differ for left- and right-handers. The primary effects will be described with respect to three variables: handedness, hand dominance, and attention. To be clear, handedness was operationally defined as where an individual falls on a continuum that ranges from −1 (*strongly left-handed*) to +1 (*strongly right-handed*) on the basis of preference scores on a battery of common tasks (Oldfield, 1971). Hand dominance is not empirically measured, rather it is assessed on the basis of the commonly held assumption that the hand of primary use is dominant in an individual and the hand of secondary use is nondominant. Thus, by convention, the right hand is dominant and the left hand is nondominant in right-handers, and the opposite holds for left-handers. Effects of attention refer to differential performances on the attended and unattended tasks. Those are discussed for both visual and nonvisual attention manipulations.

The novel effects in this experiment relate to mean radius, which was used as an approximation of circle size. As predicted, visual attention to one task resulted in larger circles for the attended than for the unattended task (Figure 2). A visual guidance or feedback account would predict that those effects must be mediated by vision. Alternatively, an attentional account would predict that those effects will occur when attention is focused on one task without the use of vision. The novel manipulation of nonvisual attention to one task (with eyes closed) resulted in larger circles for the attended than for the unattended task, strongly supporting an attention account for the effects on circle size. If those effects were caused by differences in an execution parameter such as movement speed or duration, then one would expect larger circles to be performed with a slower speed (longer duration) than would smaller circles. The findings revealed precisely the opposite, however, bolstering the conclusion that at least some effects of attention on circle size and shape are caused by internal processes related to representation and planning, as has been suggested by earlier findings (Franz, Eliassen, Ivry, & Gazzaniga, 1996). Those planning processes appear to be influenced by selective visual or nonvisual attention. Moreover, I purport that they are distinct from effects that arise with direct manipulations on execution processes, such as applying vibration to the muscles of movement (Verschueren, Swinnen, Cordo, & Dounskaia, 1999). Together, those results suggest that although one influence on circle size depends on internal processes of attention (that are common to both nonvisual and visual attention), a second influence might be related to processes of visual guidance during execution of the motor output. That second form would differentiate visual and nonvisual conditions because it would not be present in nonvisual attention conditions performed with eyes closed. Indeed, in an earlier study, Zelaznik and Lantero (1996) demonstrated that the scaling of size in circle drawing might be influenced by the presence or absence of vision.

As emphasized earlier, the present study involved assigning identical rather than distinct tasks to the two hands. It is therefore unlikely that the current tasks demanded more resources than were available, as has been shown in a large corpus of literature on divided attention tasks (Duncan, 1979; Kahneman, 1973; Keele, 1973). The results of previous studies on circle drawing also have suggested that in-phase symmetrical circle drawing of the type examined in the present study tends to produce stable performance regardless of the frequency of movement, again suggesting that performance demands did not exceed available resources (Wuyts et al., 1996). With respect to circle size, therefore, it would appear that some internal representation of an average size is distributed to tasks of the two hands, depending on the allocation of attention to one task or the other.

A reliable finding from this study was that visual attention to the left-hand task resulted in the most dramatic effects of size redistribution between the hands. Whereas the redistribution was particularly apparent with circle size (mean radius), it also occurred to some extent in aspect ratio (shape). Moreover, an increased phase lead of the left hand occurred when that hand received visual attention. A parsimonious account of the primary findings in this study is that the left hand normally receives nonvisual attention and the right hand normally receives visual attention. That account is consistent with the basic claims of Peters (1981, 1985), although temporal properties were emphasized in his task and he did not manipulate different types of attention. The most extreme demand of applying visual attention to the left-hand task appeared to result in the largest degree of redistribution in task properties during bimanual performance. Because I required the participants in the present study to produce otherwise identical tasks with the two hands, one can conclude that the distribution of task parameters to the two hands depends on attention allocation even in dual tasks that do not tax attentional capacities or resources beyond those normally available. The present study might be the first demonstration of a natural asymmetry in attention between the hands during a bimanual task that involves doing the same thing with the two hands.

In addition to the primary effects, a common finding across all within-hand measures was a larger variance observed for the task of the nondominant hand than for that of the dominant hand. That result was found for variance of radius, period, and aspect ratio, indicating that hand dominance strongly influenced the variance but not the means of the performance measures.

To summarize, the present findings revealed the important influence of attention in distributing task properties during bimanual performance. The most robust effects were those on circle size: Circles of the attended task were larger than circles of the unattended task. I propose that the common finding of an increase in task size observed under both visual and nonvisual manipulations reflects internal representation and planning processes that are directly influenced by attention. As indicated by the lack of interactions with group, the conclusions concerning the primary within-hand variables apply generally to both left-handers and right-handers. In addition, some comparisons between tasks of the two hands suggest that the left and right hands adopt more similar task properties overall in left-handers than in right-handers. For example, left-handers demonstrated more similarity between tasks of the two hands in measures of mean period and mean aspect ratio. In addition, left-handers showed more evidence of a mixed hand lead than did right-handers. The nature of those effects remains to be explored.

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NOTE

1. A measure of eccentricity was computed in all experiments, following Franz et al., 2002. All circles produced eccentricity values that closely approximated circularity, similar to the examples shown in Figure 1. Because that measure did not lead to any significant or meaningful results, it is not reported further. The remaining variables were those that are usually used in studies of bimanual circling because they are believed to capture basic parameters involved in the formation of continuous circle trajectories.

REFERENCES

Amazeen, E. L., Amazeen, P. G., Treffner, P. J., & Turvey, M. T. (1997). Attention and handedness in bimanual coordination dynamics. *Journal of Experimental Psychology: Human Perception and Performance, 23*(5), 1552–1560.

Carson, R. G., Thomas, J., Summers, J. J., Walters, M. R., & Semjen, A. (1997). The dynamics of bimanual circle drawing. *The Quarterly Journal of Experimental Psychology, 50A*(3), 664–683.

Duncan, J. (1979). Divided attention: The whole is more than the sum of its parts. *Journal of Experimental Psychology: Human Perception and Performance, 5*(2), 216–228.

Franz, E. A. (1997). Spatial coupling in the coordination of complex actions. *The Quarterly Journal of Experimental Psychology, 50A*(3), 684–704.

Franz, E. A. (2000a, July). *A double dissociation between callosal agenesis and callosotomy participants on a bimanual task.* Paper presented at the Forum for European Neurosciences, Brighton, United Kingdom.

Franz, E. A. (2000b, July). *A double dissociation in the cerebral dominance of bimanual control: Callosotomy versus callosal agenesis.* Poster presented at the international meeting of Attention and Performance XIX, Kloster Irsee, Germany.

Franz, E. A., Eliassen, J. C., Ivry, R. B., & Gazzaniga, M. S. (1996). Dissociation of spatial and temporal coupling in the bimanual movements of callosotomy patients. *Psychological Science, 7,* 306–310.

Franz, E. A., & Ramachandran, V. S. (1998). Bimanual coupling in amputees with phantom limbs. *Nature Neuroscience, 1*(6), 443–444.

Franz, E. A., Rowse, A., & Ballantine, B. (2002). Does handedness determine what hand leads in a bimanual task? *Journal of Motor Behavior, 34,* 402–412.

Franz, E. A., Zelaznik, H. N., & McCabe, G. (1991). Spatial topological constraints in a bimanual task. *Acta Psychologica, 77,* 137–151.

Guiard, Y. (1989). Failure to sing the left-hand part of the score during piano performance: Loss of the pitch and Stroop vocalizations. *Music Perception, 6*(3), 299–314.

Kahneman, D. (1973). *Attention and effort.* Englewood Cliffs, NJ: Prentice-Hall.

Keele, S. W. (1973). *Attention and human performance.* Pacific Palisades, CA: Brooks.

Klapp, S. T. (1979). Doing two things at once: The role of temporal compatibility. *Memory and Cognition, 7,* 375–381.

Oldfield, R. C. (1971). The assessment and analysis of handedness: The Edinburgh Inventory. *Neuropsychologia, 9,* 97–113.

Peters, M. (1981). Attentional asymmetries during concurrent bimanual performance. *Quarterly Journal of Experimental Psychology,* 33A, 171–196.

Peters, M. (1985). Constraints in the performance of bimanual tasks and their expression in unskilled and skilled subjects. *Quarterly Journal of Experimental Psychology, 37A,* 171–196.

Semjen, A., Summers, J. J., & Cattaert, D. (1995). Hand coordination in bimanual circle drawing. *Journal of Experimental Psychology: Human Perception and Performance, 21,* 1139–1157.

Stucchi, N., & Viviani, P. (1993). Cerebral dominance and asynchrony between bimanual two-dimensional movements. *Journal of Experimental Psychology: Human Perception and Performance, 19*(6), 1200–1220.

Swinnen, S. P., Jardin, K., & Meulenbroek, R. (1996). Between-limb asynchronies during bimanual coordination: Effects of manual dominance and attentional cueing. *Neuropsychologia, 34*(12), 1203–1213.

Temprado, J. J., Zanone, P. G., Monno, A., & Laurent, M. (2001). A dynamical framework to understand performance trade-offs and interference in dual tasks. *Journal of Experimental Psychology: Human Perception and Performance, 27*(6), 1303–1313.

Treffner, P., & Turvey, M. T. (1996). Symmetry, broken symmetry, and handedness in bimanual coordination dynamics. *Experimental Brain Research, 107,* 463–478.

Verschueren, S. M., Swinnen, S. P., Cordo, P. J., & Dounskaia, N. V. (1999). Proprioceptive control of multijoint movement: Bimanual circle drawing. *Experimental Brain Research, 127*(2), 182–192.

Wuyts, I. J., Summers, J. J., Carson, R. G., Byblow, W. D., & Semjen, A. (1996). Attention as a mediating variable in the dynamics of bimanual coordination. *Human Movement Science, 15,* 877–897.

Zelaznik, H. N., & Lantero, D. (1996). The role of vision in repetitive circle drawing. *Acta Psychologica, 92*(1), 105–118.

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