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Spatial Conceptual Influences on the Coordination of Bimanual Actions: When a Dual Task Becomes a Single Task

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ABSTRACT. When the left and right hands produce 2 different rhythms simultaneously, coordination of the hands is difficult unless the rhythms can be integrated into a unified temporal pattern. In the present study, the authors investigated whether a similar account can be applied to the spatial domain. Participants (N = 8) produced a movement trajectory of semicircular form in single-limb and bimanual conditions. In the bimanual tasks, 1 limb moved above the other in the frontal plane. Bimanual unified tasks were constructed so that the spatial paths to be produced by the 2 limbs could be easily conceptualized as parts of a unified circle pattern. Bimanual distinct tasks availed a less obvious spatial pattern that would unify the 2 tasks. Performance of the spatial patterns was more accurate in the unified task, despite similar demands placed on the coordination dynamics between the limbs in the 2 cases (e.g., the phase relations). The authors conclude that a dual task becomes a single task, and interlimb interference is reduced, when the spatial patterns produced by the 2 hands form a geometric arrangement that can be conceptualized as a unified representation.

Key words: bimanual coordination, complex action, dual-task interference

Although it is to our evolutionary advantage to be able to perceive more than one event at a time, it could be destructive, or at least confusing, to produce two different goal-related actions at once. That is not to say that we cannot learn to perform unrelated tasks simultaneously, as in walking and talking. Indeed, even complex bilateral motor tasks appear to become somewhat automated when well learned (e.g., Franz, Waldie, & Smith, 2000). Suffice it to say that, even if we are not fully aware of the adaptive significance of the difficulties we initially encounter in doing two different tasks at once, most of us have experienced its consequences on some level. Recall the childhood challenge of patting the head while rubbing the tummy, a task that results in seemingly uncontrollable hair-twisting and tummy-smacking gestures. A less trivial example occurs in the amateur pianist who attempts for the first time to sing a melody with a time structure that differs from the rhythm produced by keystrokes of the hands. As those examples illustrate, when performing two different actions concurrently, the quality of performance of each unitary action diminishes.

Two primarily cognitive approaches to the study of dual-task interference have been formulated. It has been assumed in studies of the psychological refractory period that serial processing of discrete responses that occur in rapid succession takes place (Broadbent, 1958; Keele, 1973; Pashler, 1990; Pashler & Johnston, 1989; Smith, 1967; Welford, 1952). The term *psychological refractory period* refers to a delay in responding to the second of two stimuli that occur in close temporal succession. The delay is thought to occur because cognitive operations dedicated to processing properties associated with the first stimulus–response task must be freed up for processing properties associated with the second task. In another approach to examining interference effects in multiple tasks, it is assumed that performance suffers when the task demands exceed the supply of available

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attentional resources (Kahneman, 1973; McLeod, 1977; Norman & Bobrow, 1975; Wickens, 1980). In those two theoretical approaches, sequential and parallel processing, respectively, are assumed.

The study of bimanual actions offers additional avenues to investigations of dual-task interference. Bimanual tasks are those that require concurrent actions of the left and right hands. In a popular approach to studying bimanual coordination, interference patterns with respect to phase relations of limb movements are examined. An in-phase relation in which two limbs (usually bilateral) move in a mirror-symmetrical fashion with respect to the longitudinal axis of the body characterizes the most stable pattern of coordination. A less stable mode occurs when the movements are performed in a 180° out-of-phase relation, referred to as *antiphase* (Haken, Kelso, & Bunz, 1985; Kelso, 1984; Semjen, Summers, & Cattaert, 1995). Those properties of phase relations are most commonly defined in relation to the joint motions of the limbs or the patterns of muscular movements involved. Such constraints may be referred to under the general classification of *egocentric*, meaning with respect to a body-centered coordinate frame (Swinnen, Jardin, Meulenbrock, Dounskaia, & Hofkens-Van den Brandt, 1997; Swinnen et al., 1998).

A second classification, also based on phase relations, is defined with respect to the direction of motion in the space external to the body. According to that coordinate frame, movements produced in the same direction in space are the most stable. Those performed in opposite directions in space are somewhat less stable. That form of constraint is referred to as *allocentric* (Baldissera, Cavallari, & Civaschi, 1982; Swinnen et al., 1997; Swinnen et al., 1998). Although egocentric constraints tend to predominate in bimanual coordination, allocentric constraints may be imposed on egocentric constraints. In such circumstances, both of those types of constraints play a role in determining the stability of coordination patterns (Swinnen et al., 1997).

In addition to constraints related to coordinate frames of reference, bimanual coordination also has been explored in the context of explicit timing processes. In one approach, researchers have manipulated the rhythmical structure of tasks, usually by employing finger-tapping paradigms. In continuous rhythmical tapping (Klapp, 1979) and in the production of discrete pairs of tapping responses by the fingers of each hand (Yamanishi, Kawato, & Suzuki, 1979), interference in the temporal patterns occurs when the two hands move with complex phase relations (e.g., 3:2 tapping frequency). Minimal interference occurs when one hand taps at a rate that is a simple harmonic of the other's tapping rate (Deutsch, 1983; Klapp, 1979; Peters, 1981). Thus, the temporal properties for the bimanual tapping movements are constrained to a single base rate. Moreover, when two nonharmonic rhythms are combined in a bimanual task, participants learn to integrate the separate rhythms into a complex polyrhythm (Jagacinski, Marshburn, Klapp, & Jones, 1988; Klapp, Nelson, & Jagacinski, 1998; Shaffer, 1981). On the basis of those results, we believe it is not the timing per se that limits performance but the constraint that there must be a unitary timing pattern. The question remains whether a similar principle can be discovered in the spatial domain.

Studies in which explicit spatial manipulations related to task demands are employed offer yet another approach to the examination of interference effects in bimanual actions. *Spatial coupling* refers to a form of interference that is observed when one attempts to produce different spatial patterns with the two hands, for example, when rubbing the tummy while patting the head. In a modified version of that task, an attempt to draw circles with one hand and lines with the other resulted in somewhat line-like circles and somewhat circle-like lines (Franz, Zelaznik, & McCabe, 1991). Spatial coupling constraints are revealed by those forms of interference observed in the spatial paths produced by each hand.

Similar effects of spatial interference are observed when participants use two different sets of muscles to perform the line–circle tasks (Franz & Ramachandran, 1998). When people attempt to produce circular motions by twirling the index finger of one hand at the same time as drawing repetitive lines with the other hand, the circles become more line-like and the lines become more circle-like. Those results suggest that one form of spatial coupling is abstract, in the sense that the effects are not linked to particular muscles.

At least one form of spatial coupling appears to be independent of peripheral feedback, as shown recently in a person who experienced a vivid phantom limb experience after amputation of one limb. When attempting to produce twirling motions of the index finger of his phantom limb while drawing linear motions by using his intact limb, that individual produced spatial interference (measured in the line tasks) that was similar to the interference observed when people with two intact limbs perform the tasks (Franz & Ramachandran, 1998). Accordingly, spatial coupling must be partially based upon central processes of planning and representation.

A form of spatial coupling is also observed in movement scale. When movements of the same general form (two circles or two lines) but different amplitudes (a small circle and a large circle, or a short line and a long line) are combined in a bimanual task, the smaller amplitude movement becomes biased toward the larger size and the larger amplitude movement becomes biased toward the smaller size (Franz, 1997; Spijkers & Heuer, 1995). A similar effect has been shown for single-joint movements with different amplitude demands (Swinnen, Walter, & Shapiro, 1988).

One of us has recently examined the neural basis of spatial and temporal coupling in the bimanual actions of people with callosotomy (Franz, Eliassen, Ivry, & Gazzaniga, 1996). Callosotomy is a medical procedure that involves surgical resection of the corpus callosum, the primary cortical connection between the two cerebral hemispheres. One task involved drawing either identical or different shapes with both hands simultaneously under reaction time conditions. Control (intact) participants demonstrated a marked slowing in reaction time and severe disruptions in the spatial characteristics of the drawings when they attempted to draw different shapes, compared with when they drew identical shapes with both hands. Those effects were eliminated in people with callosotomy. The differences between groups on the spatial coupling interactions occurred despite similar temporal coupling in the two groups on a continuous drawing task. Franz et al. inferred that the spatial effects reflect interactions that depend on the intact corpus callosum, whereas the temporal effects do not. Spatial planning and representation of bimanual movements, therefore, appear to depend on direct cortical interactions between hemispheres.

It is clear that some forms of spatial coupling are intimately linked to a body coordinate system and are therefore indistinct from egocentric constraints. Similarly, spatial constraints that operate with respect to particular spatial landmarks outside of the body may be indistinct from allocentric constraints. But there appears to be an additional classification of spatial constraints that may be more conceptual in nature, in the sense that they reflect constraints solely in the "space of the mind." Being asked to draw a circle, for example, requires that one conjure up vis á vis the mind a conceptual representation of a circle from one's internal space. As we have shown (Franz et al., 1996; Franz & Ramachandran, 1998; Franz et al., 1991), an attempt to produce two different conceptually represented spatial forms results in spatial interference effects that are not linked to particular motor systems, peripheral feedback processes, or environmental stimuli. Perhaps such spatial constraints can be considered as conceptual.

If spatial coupling (at least partially) reflects conceptual processes associated with representation in space, it seems plausible that such processes could mitigate coordination difficulties associated with unstable modes of performance. We sought to examine that possibility in the present study by manipulating the geometric patterns that described two separate tasks so that the tasks could be easily conceptualized as forming a unified pattern, or they could not be conceptualized in that way (e.g., they remained as apparently distinct tasks). Our primary objective was to ascertain whether a dual task becomes more like a single task if a unified spatial pattern can be used to represent the actions performed by both hands.

A task was developed in which movements described by semicircular patterns were to be produced under single-hand and bimanual conditions. We manipulated the orientation of the movement patterns in bimanual tasks to define distinct categories of the tasks. Those categories consisted of two separate but identical spatial patterns, two separate but distinct spatial patterns, or two separate but distinct spatial patterns that could easily be unified so that a common spatial pattern would be formed. By equating the tasks as much as possible for egocentric and allocentric coordination constraints, we could examine whether the availability of a unified spatial pattern would make it possible to overcome movement constraints associated with producing two distinct tasks at once.

In constructing those tasks, we considered one other possible confounding factor that might influence our interpretations. We realized that in standard bimanual paradigms (whether tapping, drawing, or moving levers) movements by the left hand in the space to the left of the body and movements of the right hand in the space to the right of the body are generally employed. Accordingly, the axis that demarcates task space is aligned with the midline axis of the body. That task characteristic would make it difficult to disentangle coupling effects related to conceptual processes of spatial planning from those related to egocentric constraints. We therefore sought to unconfound those two levels of constraint by employing movements that were not symmetrical with respect to the longitudinal axis of the body, but instead were organized with respect to a horizontal axis of symmetry (e.g., upper versus lower space in the frontal plane). Task manipulations therefore reflected primarily allocentric constraints.

Method

Participants

The participants were right-handed graduate and undergraduate volunteers (4 men and 4 women) between the ages of 18 and 23. All were naive to our purpose in the study, and none had previous experience as a participant in a bimanual experiment.

Apparatus

Two semicircular templates, 30 cm in diameter and 5 cm in width, were constructed out of black cardboard. The participant sat on a chair located 60 cm from each of two tripods supporting Watsmart (Waterloo, Ontario, Canada) cameras. An audio amplifier was interfaced with a Scientific Solutions 12-bit digital-to-analog converter that was installed in a Zenith ZW-248 computer. We used those to generate and produce a metronome-like pacing signal.

We placed two infrared-light-emitting diodes, mounted separately on cardboard thimbles, on the index fingers of the participant's right and left hands to register movement. The two light-emitting diodes were sampled at 250 Hz via a Watsmart infrared recording system that was interfaced with a Compaq 386/16 computer. The static calibrations for each session ranged from 2.1–3.0 mm of root mean square error (*RMSE*).

Task

All tasks involved the production of semicircles in the x–z (frontal) plane in the three-dimensional space directly in front of the body, with full vision. Semicircles were produced by moving the limb or the limbs, with the index finger or fingers extended in the space in front of the body, in a left-to-right-to-left fashion. The index finger of each limb was to traverse a semicircular path in the shape of the template or templates that were shown to the participant before each block of trials. Those movements were produced in a repetitive fashion in rhythm with a 1-Hz metronome pace (1 Hz per half cycle of the movement), for trials of 20-s duration.

Semicircular forms were produced in two orientations, forming either the top half (top) or the bottom half (bottom) of a circle. Participants were instructed to prevent trunk movements and to maintain a stable posture while performing the tasks. The experimenter stood behind the participant during all testing sessions to monitor performance and ascertain that those instructions were followed.

In bimanual tasks, one limb was to move directly above the other without the two limbs touching each other. Participants were free to choose which index finger would move in the space above the other, with both index fingers approximately the same distance from the body. In the top-top condition, the extended index finger of each hand was to produce the top half of a circle, with one moving directly above the other. In the bottom-bottom condition, the extended index finger of each hand was to produce the bottom half of a circle, with one hand moving directly above the other. Those two conditions involved spatial patterns that were identical with respect to external space. In the top-bottom condition, the extended index finger of one hand was to produce the top half of the circle above the index finger of the other hand while the other hand produced the bottom half of the circle. That bimanual task involves movements that can be easily conceptualized as forming a unified spatial pattern (i.e., a circle or doughnut), despite the requirement that the two hands produce spatial patterns in different orientations.[1] In the bottom-top condition, the index finger of one hand was to produce the bottom half of a circle in the space above the index finger of the other hand; the other hand was to produce the top half of a circle. In that condition, the two hands produced spatial patterns that differed in orientation, and the combined spatial pattern did not seem to produce an easily recognizable "shape" or "concept."

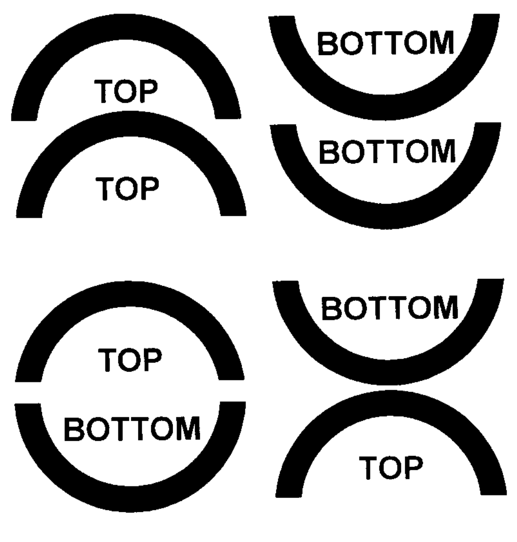

FIGURE 1. Static representation of the templates shown for the four bimanual tasks.

In Figure 1 we show the unimanual and bimanual templates that represented each task. All tasks were to be performed in the frontal plane in front of the body, with the x-axis of the task space aligned with the left–right horizontal axis of the space in front of the body and the z-axis of the task space aligned with a top–bottom axis in front of the body.

Most important, the direction of movement in space was held constant across the four bimanual task conditions, with both limbs moving together from right to left, and vice versa. We used that procedure to ensure as much as possible that postural requirements in the major dimension of motion were constant across conditions. Movement requirements along the z dimension were described by movements in the same direction in space for the top-top and bottom-bottom conditions, and in the opposite direction in space for the top-bottom and bottom-top conditions. Accordingly, we expected that the allocentric constraints prescribed by the top-top and bottom-bottom conditions would not pose difficulties for the movement system with respect to motions in the z dimension, but that movements in opposite directions that characterized the requirements in the top-bottom and bottom-top conditions might lead to less stable coordination patterns.

Because we wanted to determine the possible influence of spatial conceptual representations on coordination, the comparison between top-bottom and bottom-top conditions was critical. Those two task conditions were matched as closely as possible for coordination constraints associated with phase relations as well as for direction of movement in space but differed in whether or not a unified spatial configuration of the bimanual task could be easily formed as an internal template to guide movements.

Conditions and Design

Participants performed four single-hand conditions (each hand performed top and bottom alone) and four bimanual conditions (top-top, bottom-bottom, top-bottom, and bottom-top). There were eight trials per condition. Participants performed single-limb conditions in a randomized order and then bimanual conditions, also randomized.

Procedure

The task requirements were explained, and then the participant was asked to read and sign an informed consent form. The participant was seated in the testing chair, and the thimbles for movement registration were placed on the participant's index fingers. We showed a region of three-dimensional space to the participant by using the calibration frame of the Watsmart system (volume with dimensions 53 cm × 53 cm × 66 cm), and we ascertained whether the participant would have difficulty executing movements in that space. No adjustments were necessary for any participants.

Templates were shown to the participant in the configuration depicting the task to be performed (as in Figure 1). Participants were instructed to maintain a spatial representation of the template or templates in memory so that it would internally guide the repeated cycles of movement within the 20-s trial. The templates were removed before the trial began.

A trial began by a verbal "ready" signal from the experimenter. The metronome beat then began, and the participant performed the assigned task condition. The metronome paced the entire trial of 10 full cycles (20 s) of continuous movement. A trial ended with the last metronome tone, and a 20-s break was given before the next trial. Two minutes were given between conditions. The testing session for each participant lasted approximately 1 hr.

After completion of the tasks, participants were asked the following questions: (a) Which condition(s) did you find to be the most difficult? (b) What was it that made the condition(s) difficult or easy? (c) Did you develop any strategies to aid in your performance?

Data Reduction

The kinematic position data were digitally filtered (Butterworth filter), forward and backward, at a cut-off frequency of 6 Hz. We generated velocity measures by using a three-point central difference technique. We then employed numerical algorithms constructed from displacement profiles (x and z) or velocity profiles to compute other dependent variables, which will be described in turn in the following section.

Results

Qualitative Results

Close examination of qualitative plots indicated that movements in all single-limb conditions appeared to be easy to produce. Few deviations from the semicircular spatial paths were obvious from viewing plots of repeated trajectories within a trial. Prototypical plots of displacement in the x–z dimensions in unimanual and bimanual conditions for a typical participant are depicted in Figure 2. As can be seen, the patterns maintained semicircular forms in all unimanual conditions. Patterns tended to maintain semicircular forms in bottom-bottom, top-top, and top-bottom bimanual conditions, but they were quite irregular in bottom-top conditions. Those observations generally held for all participants.

Displacement in each dimension (x and z) over time was plotted for all conditions. Figure 3 depicts representative plots of the x displacement and the z displacement over 16 s in time for each unimanual condition produced by a typical participant. As can be seen, the patterns produced in single-limb conditions for both top and bottom semicircles were of the same general form. Figure 4 depicts representative plots of both dimensions in the bimanual conditions performed by the same participant. In the top-top and bottom-bottom conditions, semicircular movements of similar forms for the two limbs were produced in both the x and the z dimensions. In contrast, the patterns produced in the top-bottom and bottom-top conditions revealed substantial irregularities in the displacement versus time profiles.

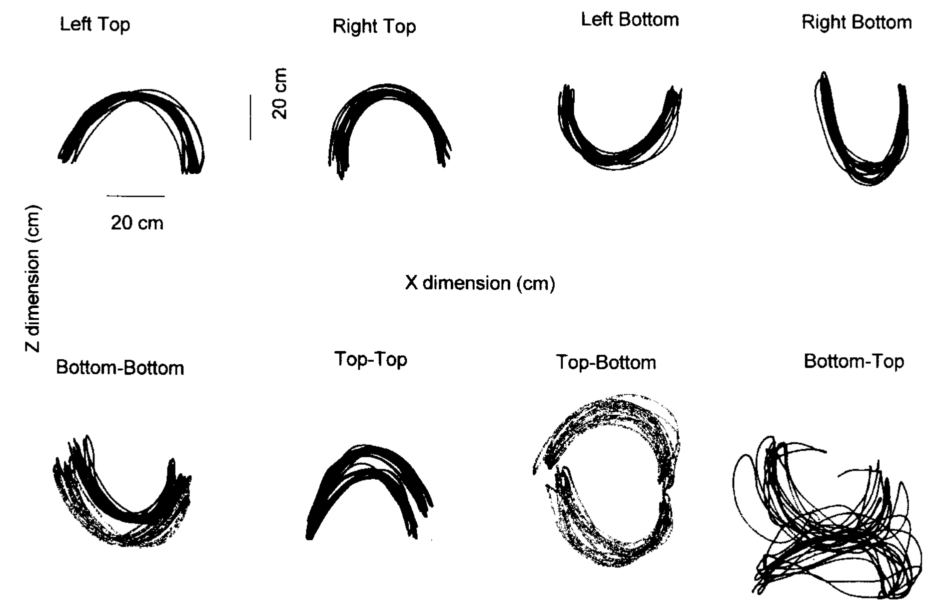

FIGURE 2. Typical x–z displacement paths for the middle 16 s of a trial for 1 participant in all conditions. The top row depicts unimanual conditions, and the bottom row depicts each hand in bimanual conditions. Note the less coherent spatial pattern in the bottom-top conditions. That result was typical for all participants.

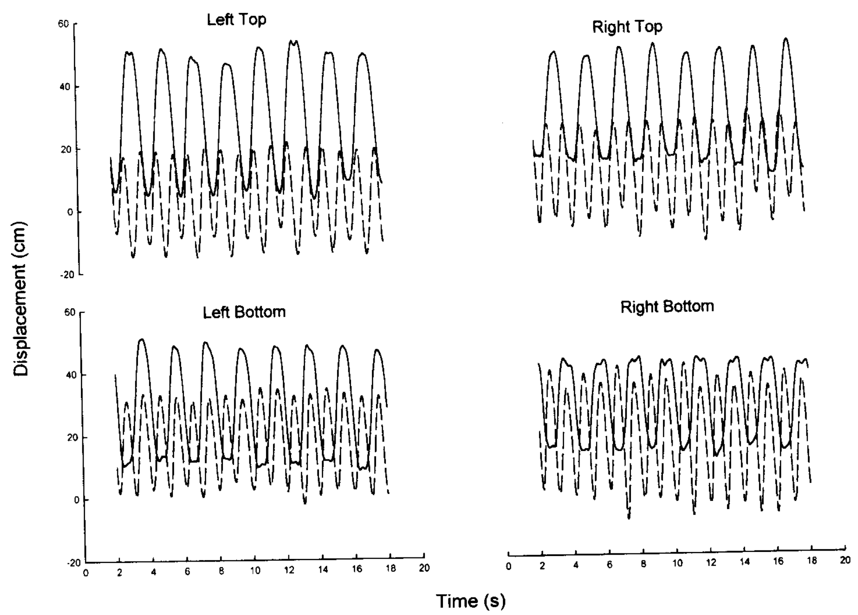

FIGURE 3. Displacement–time trajectories x (solid line) and z (dashed line) for a typical participant in unimanual conditions.

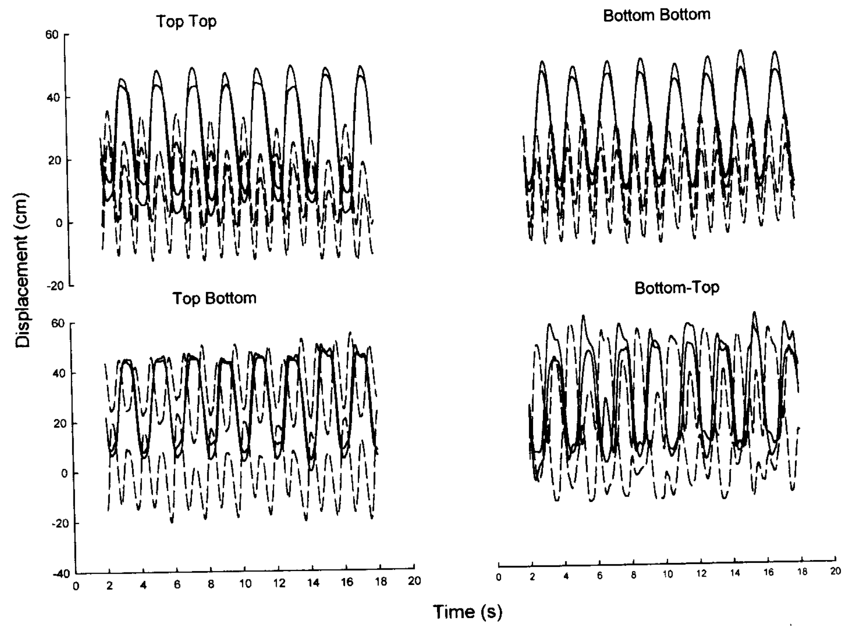

FIGURE 4. Displacement–time trajectories x (solid line) and z (dashed line) for both hands of a typical participant in bimanual conditions.

The global pattern described by the spatial path of the movements over all cycles was observed from plots of the x versus z displacement over time. The global spatial pattern revealed very little interference in the top-top and bottom-bottom conditions. Interference also appeared to be minimal in the global spatial pattern of the top-bottom condition in comparison with the bottom-top condition. Specifically, in the bottom-top condition, the global spatial pattern did not resemble semicircular patterns on 80% of the trials across participants. Rather, the patterns revealed marked deviations from semicircular paths. Spatial disruptions of that type are a hallmark of trajectory interference that occurs with the attempt to coordinate movements with different spatial forms (i.e., Franz, 1997; Franz et al., 1991). A representative trial that illustrates the higher degree of interference that occurs in the bottom-top condition relative to the top-bottom condition, is shown in Figure 2.

Results of Interviews

All participants except 1 indicated that the bottom-top condition was the most difficult to produce. Of those, 2 participants found the bottom-top condition impossible to perform, but they could not describe exactly why. Both, however, alluded to "picturing something common." Four participants explicitly indicated that the top-bottom condition was easier to produce than the bottom-top condition (those were not labeled as such for the participants) because in the top-bottom condition they could "think of a circle."

Quantitative Analyses of Coupling Effects

Although the kinematic profiles revealed that the bottom-top condition appeared to be the most difficult for participants to produce, our qualitative observations of the displacement profiles of both the x and the z dimensions across time revealed that the peaks tended to be aligned for the two hands, suggesting a tight coupling between the limbs. To further examine those effects, we performed a relative phase analysis on data of 7 out of 8 participants (data of the last participant were lost because of a computer error).

We used the displacement and velocity records for the middle 16 s of each trial to quantify phase relations between the limbs. Those records were normalized to the standard (z) distribution over the entire 16 s and then "sliced" into eight 2-s intervals. We calculated phase in x and z of the path produced by each hand by computing the inverse tangent function of the ratio of normalized velocity to normalized displacement for each dimension. We calculated between-hands relative phase by subtracting the value obtained for one hand from that obtained for the other, for the two respective dimensions of motion.

For each 2-s interval, median between-hands relative phase and the standard deviation were computed. Those results were entered into analyses of variance (ANOVAs) in which the variables condition (4) and interval (8) were repeated over trial. For median between-hands phase, a main effect of condition was found in both the x and the z dimensions, $F(3, 18) = 4.10$, $p < .05$, for the x dimension, and $F(3, 18) = 19.46$, $p < .001$, for the z dimension. Similar effects were obtained for the standard deviation of that measure, for both the x dimension, $F(3, 18) = 9.29$, $p < .001$, and the z dimension, $F(3, 18) = 7.63$, $p < .002$. Because we did not, a priori, hypothesize which conditions would differ, we employed Newman-Keuls multiple comparison procedures (as opposed to planned comparisons) to further assess those main effects. For the median relative phase, the critical difference required to reject the null hypothesis was 21.1° for the x dimension and 51.26° for the z dimension. Values in both dimensions of the bottom-top and top-bottom conditions were significantly different from values in both dimensions of the top-top and bottom-bottom conditions by a magnitude greater than the critical value (all $ps < .05$). Bottom-top and top-bottom did not differ from each other in those measures of between-hands phase, nor did top-top and bottom-bottom differ from each other (both $ps > .05$). Statistical reliability of effects on the standard deviation of those values was similar in all respects to the effects on the median. The standard deviation of median relative phase for all conditions across the eight time intervals is shown in Figure 5.

Those analyses confirmed our qualitative observations that the top-top and bottom-bottom conditions were more

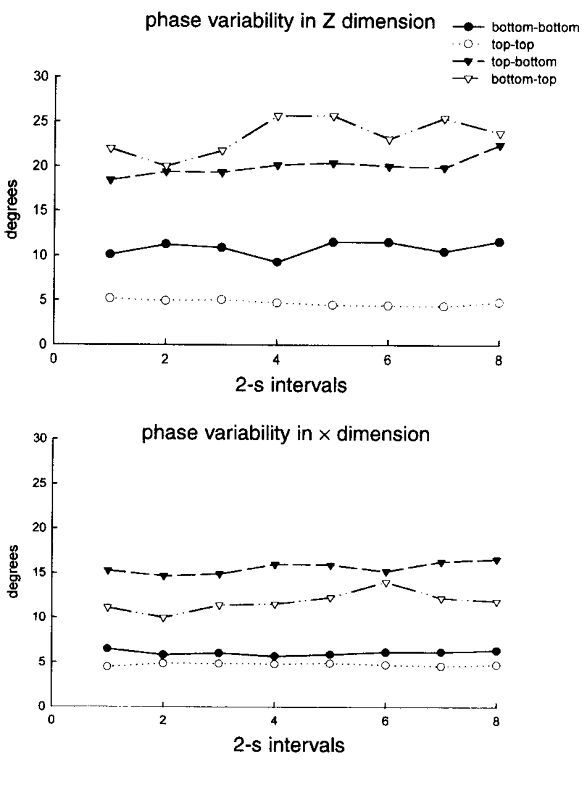

FIGURE 5. Standard deviation in median relative phase for the z (**top panel**) and x (**bottom panel**) dimensions as a function of bimanual condition and 2-s interval.

stable than the top-bottom and bottom-top conditions in the between-hands coupling of the limbs. There were no significant main effects or interactions of trial or interval for either dependent variable (all *p*s > .05).

To examine the claim that the top-bottom condition was easier to perform than the bottom-top condition because of the availability of a unified spatial pattern in the former but not the latter condition, we performed a final analysis to assess the spatial constancy of the produced trajectories. If an individual were drawing a perfect circle with an unchanging center, the radius of any point along the path of that circle would be equal to the radius at any other point on the path. In other words, the standard deviation of the collection of radii computed from any trajectory should approach zero. Larger standard deviations would imply greater spatial variability in the shape of the trajectory. We determined the center of each circle of the semicircle by averaging all points on the trajectory. Then for each kinematic sample we computed the radius of that point from the center. In the bimanual conditions, there were two sets of radii, one for each hand. The standard deviation in the individual sets of radii and their mean were computed. In the bimanual conditions, we additionally computed the ratio of the two radii on a sample-by-sample basis and then calculated the average ratio and standard deviation across the two hands.

Because comparisons across bimanual conditions (particularly between top-bottom and bottom-top) were a priori planned, within-subject contrasts were applied to the standard deviations of the computed ratios. In bottom-bottom (*SD* ratio = 2.95) and top-top (*SD* ratio = 2.78) conditions, the least variable shapes were produced, and they did not differ from each other, $F(1, 6) < 1.0$. Those two conditions did not differ from top-bottom (*SD* ratio = 3.49), both $Fs(1, 6) < 3.5$, $p > .05$. Most important, less variable shape constancy was produced in all three of those conditions than in the bottom-top (*SD* ratio = 4.66) condition, all $Fs(1, 6) > 7.78$, $p < .05$. The findings in the spatial domain provided quantitative support for our hypothesis that the degree of spatial disruption in the bottom-top condition would be greater than that observed in the top-bottom condition.

Discussion

In this experiment we examined whether we could use a unified spatial conceptual pattern to reduce dual-task interference in a bimanual task, making a dual-task more like a single task. Phase relations with respect to a body coordinate frame (egocentric) and with respect to movement direction in extrinsic space (allocentric) were manipulated so that they would be identical for both unified and distinct bimanual tasks; our objective was to observe effects of cognitive planning and spatial representation separately from effects related to the egocentric and allocentric properties that govern the motor coordination of the limbs.

We found that interference was larger in tasks characterized by opposite direction motions in the *z* dimension than in tasks requiring same direction motions in the *z* dimension. That constraint appears to have distinguished top-bottom and bottom-top conditions from top-top and bottom-bottom conditions on the basis of allocentric constraints. In addition, trajectories in the top-bottom, top-top, and bottom-bottom conditions were significantly less variable in terms of their spatial quality than those produced in the bottom-top condition. More important, unlike the other conditions, we manipulated the bottom-top condition so that it would consist of two distinct tasks that could not be easily conceptualized as forming a unified (or identical) spatial pattern.

Together these findings lead us to infer that there are two qualitatively different types of interference, one that appears to be related to a representation of the spatial conceptual pattern and the other that appears to be related to the coordination constraints associated with the movement dynamics of the limbs. We propose that the availability of a global spatial conceptual pattern may mediate, in large part, the extent to which cognitive control can overcome those movement-related constraints.

Notably, the bottom-top condition was characterized by two distinct spatial patterns oriented differently in space, as opposed to either two identically oriented spatial patterns (as in the top-top and bottom-bottom conditions) or two spatial patterns that form a unified spatial conceptual pattern (top-bottom condition). In addition to those differences, in the bottom-top condition, unlike the other conditions, the two hands had to begin and end each cycle of movement from spatial locations that were far apart from one another. The other three conditions appear to share the property that the two hands were in relatively closer proximity to one another at the beginning and end of each cycle of movement. It is not yet known whether people cognitively represent the entire global pattern or whether they cognitively represent points in space that would correspond to particular features of the pattern of a familiar spatial geometry projected onto space. Although the two strategies cannot be differentiated at this time, both appear to reflect cognitive processes associated with spatial representation.

We put forth the suggestion that at least two levels of processes are operating. One level is related to cognitive conceptual processes involved in spatial representation. The other level is related to the properties of coordination dynamics between the limbs. The between-hands analyses of phase indicated that coupling between the limbs was the same across top-bottom and bottom-top conditions, although those two conditions differed from top-top and bottom-bottom conditions. More important, however, the two limbs were closely coupled in the top-bottom and bottom-top conditions, despite the compromised spatial constancy apparent in the latter relative to the former.

We manipulated the bimanual tasks so that a global spatial pattern could be easily conceptualized in the top-bottom condition but not in the bottom-top condition. However, we manipulated the required phase relations between the limbs so that they would be as similar as possible. A superior spatial quality of the trajectories in the top-bottom condition was observed, despite similar coupling in the phase relations between the hands in the two conditions. Those main findings lead us to infer that people are able to overcome some of the interference effects associated with an intrinsically lower stability in bimanual coupling when they can use a unified spatial pattern to guide the spatial paths of the hands. Because in the present study we employed tasks with top-bottom horizontal symmetry rather than the typical left-right mirror symmetry, one could argue that people may tend to give up the natural preference to produce in-phase movements that characterize the most stable mode of coupling (related to an egocentric coordinate frame) and switch to a preference to move the limbs with respect to a representation of external coordinate space (an allocentric coordinate frame).

One might consider the case in which the motor coordination constraints do not produce interference in the bimanual task. Suppose, for example, that the top-bottom and bottom-top tasks were modified so that they were performed in the 90° rotated orientation of the tasks performed in the present study. Rotating the figures 90° would produce bimanual tasks that are mirror-symmetrical with respect to the vertical body axis. In essence, the tasks would no longer be aligned in terms of allocentric constraints, but with respect to the more predominant egocentric constraints. Relying on the plethora of findings reported in the literature on movements of this type (vertically symmetrical bimanual tasks), the results of this experiment are completely predictable, and one can demonstrate that by actively doing the task. Both the top-bottom and bottom-top 90° rotated tasks are now easy to produce, given that they both are characterized by in-phase relations with respect to egocentric space.

As the previous example illustrates, without demands on cognitive representation, people may be able to resort to a preferred mode regulated by constraints associated with the bilateral symmetry of the body. One possible model of the present effects is that people may coordinate their limbs with respect to one type of coordinate space at a time. When necessary, people may switch from one coordinate space to another. The switch may be facilitated through the use of cognitive processes such as the conceptual processes demonstrated herein. Alternatively, the different coordinate spaces may be arranged hierarchically so that the processes that operate at one level (e.g., the cognitive representational level) can override processes that operate at another level (e.g., the motor coordination constraints). Our results do appear to imply that if a person performs movements or patterns that comply with the most preferred and stable preexisting coordination modes, cognitive penetration may not be required. Moreover, if different tasks can be conceptualized as being parts of a unified task through cognitive strategies, then interference associated with the dual-task will diminish. The dual-task becomes more like a single task.

Recent findings of Klapp et al. (1998) support a similar notion with respect to the time domain of rhythmic tapping tasks. Skilled performers are able to produce what appear to be very complex differentiated rhythms with the two hands because they are able to integrate different nonharmonic rhythms into a complex polyrhythm (for other examples, see Deutsch, 1983, Jagacinski et al., 1988, Peters, 1977, 1981, and Summers, Todd, & Kim, 1993).

In sum, we conclude that a common spatial representation can be used to guide the movements of the two limbs in a bimanual task. That strategy may enable participants to overcome at least some of the constraints that are inherent at other levels of control. Such strategies may serve to reduce interference associated with performing two tasks at once. In addition to its application in producing complex temporal rhythms and spatial patterns through multiple output systems, this principle may be applicable to multitask situations generally. Just as we are unable to perform two different actions concurrently with high fidelity (without significant practice), we appear (for the most part) to be unable to entertain two unrelated thoughts concurrently. Accordingly, integrating separate task components into a single representation (a concept) may be functionally equivalent to maintaining one thought, or cognitive set, at a time.

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NOTE

1. Ten judges, naive to our purpose in the experiment, independently rated the bottom-top condition as the only one that could not be conceptualized as a single configuration. Two of those judges claimed that the pattern most closely resembled a Chi-square symbol, but that configuration was not one that would easily come to mind. All judges agreed that the other three conditions were easily conceptualized as either half a circle or a single circle.

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Note From the Editors

We wish to express our gratitude to Aftab Patla, who is stepping down after serving with distinction for 6 years as Executive Editor of the *Journal of Motor Behavior.* His outstanding efforts on behalf of the journal are greatly appreciated, and he will continue to serve as an Editorial Board member. We thank our Consulting Editors and Editorial Board who assisted in the search for a new Executive Editor, and welcome Timothy D. Lee, who has agreed to serve in that capacity. We look forward to working with him.

In addition, we welcome new Consulting Editors Martha Flanders, Elizabeth A. Franz, Gerald Gottlieb, Neville Hogan, Jürgen Konczak, and Robert L. Sainburg.