When two limbs are weaker than one: Sensorimotor syncopation with alternating hands

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This study addresses the demands of alternating bimanual syncopation, a coordination mode in which the two hands move in alternation while tapping in antiphase with a metronomic tone sequence. Musically trained participants were required to engage in alternating bimanual syncopation and five other coordination modes: unimanual syncopation where taps are made (with the left or right hand) after every tone; unimanual syncopation where taps are made after every other tone; bimanual synchronization with alternating hands; unimanual synchronized tapping with every tone; and unimanual tapping with every other tone. Variability in tap timing was greatest overall for alternating bimanual syncopation, indicating that it is the most difficult. This appears to be due to instability arising from the simultaneous presence of two levels of antiphase coordination (one between the pacing sequence and the hands, the other between the two hands) rather than factors relating to movement frequency or dexterity limits of the nonpreferred hand.

More often than not, different movement sequences can be used to produce the same basic action outcome or effect. For example, a percussionist may play a series of quarter notes by striking a drum either with one hand (right–right–right–right) or with both hands in alternation (right–left–right–left). A similar situation arises in studies of motor coordination wherein participants are required to produce an isochronous sequence of finger taps using either one hand (*unimanual*) or two alternating hands (*bimanual alternation*). In these studies, the variability in intertap intervals (ITIs) is typically used as an index of performance stability. It has been found that at moderate rates (e.g., when the target base ITI is 500 ms) ITI variability is commensurate for bimanual alternation and unimanual tapping (Semjen & Ivry, 2001; Yamanishi, Kawato, & Suzuki, 1980), whereas at relatively fast rates (200–400-ms target ITIs)

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variability is greater for bimanual alternation than for unimanual tapping (Wing, Church, & Gentner, 1989).[1] In fact, at very fast rates, bimanual alternation collapses, and the two hands start tapping synchronously with one another (MacKenzie & Patla, 1983). This phenomenon also occurs in the context of alternating movements that do not involve collision with a solid surface, such as the flexion-extension of fingers (Kelso, 1984; Mechsner, Kerzel, Knoblich, & Prinz, 2001), wrists (Kay, Kelso, Saltzman, & Schöner, 1987), or forearms (Beek, Rikkert, & van Wieringen, 1996). The common elements across these tasks are the intended antiphase relationship between two effectors—the movement trajectory of one effector lags behind the trajectory of another effector at a phase distance of half a cycle—and its increasing instability as the rate of movement increases.

Antiphase coordination occurs not only between effectors within an individual (action–action coordination), but also in situations where an individual must produce movements in alternation with an external (more or less) isochronous pacing signal (perception–action coordination). For example, if our percussionist were to join a marching band, then he or she may be required to strike a snare drum repeatedly at the midpoint between beats marked by the bass drum player. Similarly, in laboratory-based *sensorimotor syncopation* paradigms, the participant is instructed to tap a finger at the midpoint between successive "clicks" of a (visual or auditory) metronome. As with bimanual alternation, there is a tendency for phase drift to occur during sensorimotor syncopation at fast rates: Tap placement drifts from the prescribed antiphase relationship to an in-phase relationship where taps and metronome clicks coincide (Fraisse & Ehrlich, 1955; Vos & Helsper, 1992). The critical rate—measured here in terms of the interonset interval (IOI) of metronome clicks—at which antiphase performance collapses to the in-phase mode during syncopation varies markedly between individuals, with critical IOIs ranging between about 275 and 1,000 ms (Fraisse & Voillaume, 1971; Kelso, DelColle, & Schöner, 1990; Volman & Geuze, 2000). In general, however, phase drift is observed at slower rates during sensorimotor syncopation than during bimanual alternation. (Rough estimates of the average rate limits of syncopation and bimanual alternation, based on the studies cited above, are 400 ms for IOI and 200 ms for ITI, respectively.)[2]

Investigators who take a dynamical systems approach to human movement have argued that the tendency to drift from the antiphase to the in-phase coordination mode during both bimanual alternation and sensorimotor syncopation indicates that the in-phase mode is the only stable mode at fast rates (Haken, Kelso, & Bunz, 1985; Kelso, 1995; Kelso et al., 1990). According to the dynamical approach, stability is determined by the strength of the coupling between oscillatory processes occurring within an individual and his or her environment. The coupling of oscillator-based timing mechanisms within the individual facilitates the

[1]Note that bimanual alternation is a different coordination mode to bimanual unison tapping, which is typically found to be more stable than unimanual tapping (e.g., Helmuth & Ivry, 1996).

[2]A caveat to keep in mind when interpreting these figures is that studies of sensorimotor syncopation necessarily employ a pacing signal, whereas studies of bimanual alternation usually do not. The presence of a pacing signal may generally increase the stability of antiphase coordination. A further point worth mentioning is that participants are typically not told to resist drifting from antiphase to in-phase in phase transition studies (e.g., Kelso et al., 1990), which may result in higher threshold estimates than if instructions stipulate to resist such drift. The modality of the metronome—auditory or visual—is another potentially influential factor that varies between studies. (For comparisons of tap timing variability with auditory versus visual pacing signals, see Kolers & Brewster, 1985; Repp & Penel, 2002; Semjen & Ivry, 2001.)

coordination of periodic multieffector movements, such as bimanual alternation, whereas coupling between the oscillations of an internal timing mechanism and periodicities in the environment sets the stage for sensorimotor coordination modes such as synchronization and syncopation. Coupling strength is influenced by the frequency of the oscillators, decreasing as frequency increases (Haken et al., 1985; Large & Jones, 1999; Peper, Beek, & van Wieringen, 1995; Sternad, Turvey, & Schmidt, 1992; Treffner & Turvey, 1993). Although in-phase coordination remains stable with weak coupling, antiphase coordination becomes unstable. Thus, antiphase coordination drifts to the in-phase mode as rate is increased. In dynamical systems terminology, the in-phase mode serves as an attractor state to which movements are drawn.

Alternatives to the dynamical approach identify factors besides oscillator coupling strength that can affect the stability of antiphase movement. For instance, interval-based approaches postulate that sensorimotor syncopation involves a single timekeeper with a base interval whose duration is half the metronome IOI (Semjen, Schulze, & Vorberg, 1992; Vos & Helsper, 1992). Thus, for each successive IOI (demarcated by two metronome clicks), one "tick" of the timekeeper occurs synchronously with the initial metronome click, and a second tick occurs at the midpoint between clicks, effectively subdividing the IOI into two equal parts. Under these circumstances, sensorimotor syncopation is achieved when only the second timekeeper tick is programmed to coincide with movement. In a similar vein, interval-based approaches assume that bimanual alternation is driven by a single timekeeper that issues motor commands alternately to the left and right hands (Semjen & Ivry, 2001; Wing et al., 1989).

The involvement of only one timekeeper in interval-based conceptions of antiphase movement logically denies a role for coupling strength. In its place emerge factors such as rate limits in cognitive-motor processing and increased timing variability (e.g., ITI standard deviation) due to the number of effectors involved, their identity, and their movement frequency (i.e., how many timekeeper intervals occur between movements). Cognitive-motor rate limits affect sensorimotor syncopation when—at fast rates—pinpointing the temporal goal (i.e., the mid-IOI timekeeper tick) of the movement becomes difficult due to insufficient processing time (Semjen et al., 1992). Likewise, in bimanual alternation, the gating mechanism that directs motor commands to alternate hands may be rate limited and hence compromised at fast rates (Ivry & Richardson, 2002). In addition, relatively high timing variability may be associated with bimanual alternation because each hand moves at half the frequency with which it would move during unimanual tapping, and such reductions in movement frequency have been shown to increase variability in accordance with Weber's law (Ivry & Hazeltine, 1995; Peters, 1989). Note that this prediction should hold only if each hand is driven by a separate timekeeper, for it is the timekeeper variance that increases as frequency decreases (Wing, 1980). However, if both hands are driven by a single timekeeper, then there is no reason to expect an increase in timekeeper variability, although the alternating hand assignment could contribute some variability of its own. Finally, the involvement of the nonpreferred hand (the left hand, for right-handed individuals), which is typically weaker in terms of timing control and dexterity (Peters, 1980; Truman & Hammond, 1990), adds to variability (Peters, 1985; Semjen et al., 1992) and may be more susceptible than its counterpart to phase drift during bimanual alternation (see Byblow, Chua, & Goodman, 1995).

The present study is concerned with a hybrid coordination mode in which bimanual alternation and syncopation are combined. Such a situation would arise, for example, if our percussionist were to play off-beats using alternating hands. To our knowledge, this form of double antiphase, or *alternating bimanual syncopation*, has not been studied previously.[3] Given that syncopation is, in general, less stable than synchronization, it seems obvious that alternating bimanual syncopation should be more difficult than alternating bimanual synchronization. However, it is less clear whether alternating bimanual syncopation should be more difficult than unimanual syncopation, and, if it is, for what reasons. The main aim of the current study is to investigate the difficulty of alternating bimanual syncopation relative to unimanual syncopation, and a subsidiary aim is to identify some of the potential reasons why a difference in difficulty might be expected.

Adopting the dynamical systems perspective leads to the expectation that alternating bimanual syncopation will be more difficult than unimanual syncopation because the added level of antiphase coordination (between the two hands) makes the system less stable overall. Specifically, the potential for phase slippage that is present during unimanual syncopation due to antiphase coupling at the level of the perception–action (metronome–hand) collective is augmented by the introduction of another level of antiphase coupling in the action–action (left hand–right hand) collective. Alternatively, interval-based approaches would attribute any disadvantages associated with alternating bimanual syncopation to either (1) motor gating constraints, (2) the lower movement frequency in each hand, (3) the involvement of the non-preferred hand, or (4) an interaction of these factors.

The experiment reported here used a finger-tapping paradigm to investigate the stability of alternating bimanual syncopation relative to five other coordination modes, giving a total of six experimental conditions (see Figure 1). Stability was indexed by measuring variability in tap timing. Apart from alternating bimanual syncopation (starting with the left or the right hand), two other syncopation modes were tested. One was the standard version of unimanual syncopation, where taps are made—with the left or the right hand—after every tone. The other was "unimanual-skip" syncopation, wherein participants tapped with one hand (left or right) but omitted a tap after every other tone. Three corresponding modes of synchronization were also tested: bimanual synchronization with alternating hands, and unimanual synchronized tapping with every tone, and unimanual-skip tapping with every other tone. The synchronization and syncopation conditions differed only in terms of the required phase relationship between taps and tones: in-phase or antiphase, respectively. Naturally, in accordance with previous research, we expected that tap timing variability would be generally higher during syncopation than during synchronization.

By allowing us to compare how alternating bimanual syncopation and synchronization each relate to their unimanual counterparts, the current design addressed whether the requirement to use two alternating hands affects variability similarly during syncopation and synchronization. We expected that both alternating bimanual syncopation and synchronization would be associated with higher variability than their standard unimanual relatives—that is, tapping either after (syncopation) or with (synchronization) every tone. If this turns out to be the case, then it should be possible to gain insight into why this is so by comparing bimanual alternation with the unimanual coordination modes that require tapping either after or with every other tone (unimanual skip). In unimanual-skip tapping, each hand is required to do in

[3] A very different form of double antiphase, involving spatial rather than temporal antiphase relationships, was studied by Byblow et al. (1995, Exp. 2).

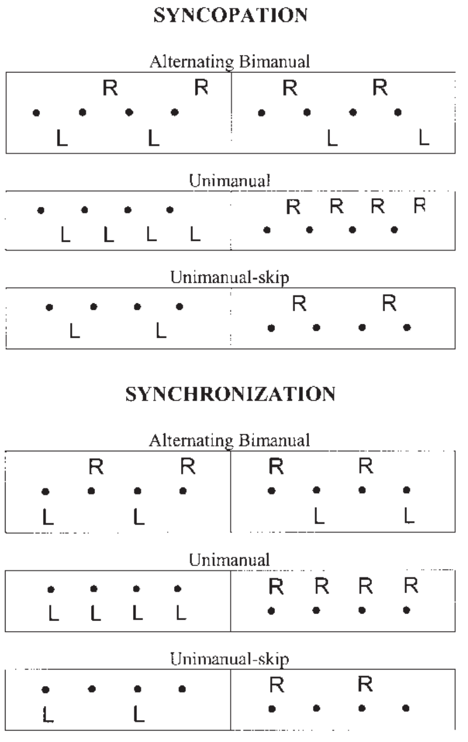

Figure 1. Schematic diagrams illustrating the coordination modes under investigation. Three syncopation modes—alternating bimanual syncopation, (standard) unimanual syncopation, and unimanual-skip syncopation—are shown in the top half of the figure, and three corresponding synchronization modes are shown in the bottom half. Dots represent tones in the pacing sequence, and "L" and "R" represent finger taps made by the left and right hands, respectively.

isolation exactly what it does together with the contralateral hand during alternating bimanual tapping. Therefore, if the lower movement frequency in each hand contributes to higher variability during bimanual alternation, then variability should be commensurate across bimanual alternation and unimanual-skip conditions. However, if heightened variability derives from the antiphase component of bimanual alternation, then variability should be lower in the unimanual-skip conditions, wherein antiphase requirements are reduced (unimanual-skip syncopation) or absent (unimanual-skip synchronization). We were unsure whether to expect that syncopation and synchronization would differ in this regard.

It was not clear whether tap timing variability should be expected to be lower in the unimanual-skip conditions than in the standard unimanual conditions: Although the reduced movement frequency resulting from skipping every other tap may increase the stability of antiphase coordination at a given sequence rate, it also is likely to increase timekeeper variability (Wing, 1980), which has the opposite effect. Moreover, the strategy of withholding taps may involve cognitive effort that increases the difficulty of the task.

The potential costs associated with using the nonpreferred hand during alternating bimanual syncopation were assessed by comparing tap timing variability for the left and right hands across all conditions. In general, greater tap timing variability was expected to be observed when tapping with the nonpreferred hand. Whether the nonpreferred hand plays a special role during alternating bimanual syncopation was an open question. Finding disproportionately higher tap timing variability for the left than the right hand in the alternating bimanual syncopation condition than in other conditions would suggest that lower dexterity in the nonpreferred hand constrains performance. Conversely, finding no such difference would suggest that hand-specific dexterity is not a major concern in alternating bimanual syncopation. We were not sure whether to expect a smaller difference between tap timing variability for the left and right hands in the unimanual-skip conditions than in the standard unimanual conditions, but we did expect a difference in favour of the preferred hand in both conditions. Likewise, it was uncertain whether the effects of preferred versus nonpreferred hand would differ for syncopation and synchronization.

Finally, sequence presentation rate was manipulated by asking each participant to estimate his or her just-manageable rate for unimanual syncopation and alternating bimanual syncopation—we expected the latter to be slower than the former—and then running all conditions at each of the two rates. We expected that variability would be higher at fast rates than at slow rates for syncopation (i.e., as the critical antiphase to in-phase transition region was approached), but that the reverse would be the case for synchronization (where increases in rate have been shown to decrease variability, as long as the limit of in-phase synchronization is not approached; see Repp, 2003).

EXPERIMENT

Method

Participants

The 8 participants included both authors in addition to 5 women and 1 man who were regular paid participants in various finger-tapping experiments. Ages ranged from 18 to 31 years, except for 2 participants who were aged 57 years. All had substantial musical training (9 or more years of study of one or more of various wind, keyboard, and stringed instruments) and preferred to tap with the right hand.

Design

A 2 × 3 × 2 × 2 repeated measures design was employed, with the variables of phase (synchronization, syncopation), mode (unimanual, unimanual-skip, bimanual-alternating), hand (left, right), and rate (slow, fast). In the case of bimanual alternation, the hand variable refers to which hand leads.

Materials

Isochronous auditory sequences were produced on a Roland RD-250s digital piano under control of a program written in MAX running on a Macintosh Quadra 660AV computer.[4] Each sequence consisted

[4]Due to a peculiarity of MAX, sequences were presented 2.4% faster than specified in the program, and tap timing was recorded 2.4% slower than it actually occurred. Actual timing values can be obtained by multiplying the reported values by 0.967. Apart from this constant scaling factor, timing in MAX is accurate to within 1 ms.

of an isochronous series of 54 identical moderately high-pitched digital piano tones (C6, 1046.5 Hz, with duration 80 ms plus damped decay). Sequence rate was set to be slow or fast by the participants themselves (see below).

Procedure

Participants sat in front of the Macintosh computer, listened to the sequences over Sennheiser HD540 II earphones at a comfortable intensity, and tapped on a Roland SPD-6 electronic percussion pad, which was held on the lap. The touch-sensitive rubber surface of the SPD-6 is divided into six segments, arranged in two rows of three. Right-hand taps were made on the top right segment and left-hand taps on the top left segment. The sensitivity of the pad was set to the manual (as opposed to drumstick) mode. Participants tapped with the index finger (in one case, with the middle finger). Some participants rested their hand on the pad and tapped by moving only the finger; others tapped "from above" by moving the wrist and/or elbow joints of the free arm. The impact of the finger on the pad provided some auditory feedback (a thud), in proportion to the tapping force; the digital sound output of the pad was turned off.

The experiment was run across two 1-hr sessions separated by approximately one week. At the start of the first session, the participant was asked to estimate his or her "just-manageable" rate for unimanual syncopation with the preferred (right) hand by tapping along with, and adjusting the presentation rate of, an isochronous pacing sequence composed of tones with the same pitch and duration characteristics as those in the 54-tone sequence described above. The participant indicated that he or she was ready to begin tapping by pressing the spacebar on the computer keyboard, which triggered a single, continuous presentation of the sequence after a brief delay. Initially the IOI was set to 800 ms. Sequence rate could subsequently be adjusted by pressing the "up" and "down" arrow keys on the computer keyboard. Pressing the "up" key shortened the IOI by a constant 20 ms, resulting in a rate increase, while pressing the "down" key lengthened the IOI by 20 ms, resulting in a rate decrease. The participant was instructed to increase the rate of the sequence until he or she could no longer tap along in antiphase, and then to decrease the rate gradually until antiphase tapping was just manageable. Clicking a virtual button on the computer screen then stopped the sequence, and the participant's estimated threshold was recorded by MAX.

Following the informal threshold estimation procedure, the participant completed six blocks, one per Phase × Mode condition. Block order was the same for each participant: (1) unimanual synchronization; (2) unimanual-skip synchronization; (3) alternating bimanual synchronization; (4) unimanual syncopation; (5) unimanual-skip syncopation; and (6) alternating bimanual syncopation. A diagram similar to one of those in Figure 1 remained on screen throughout the block. Each block contained 12 (2 practice + 10 test) trials, each consisting of a single presentation of the 54-tone sequence at the rate selected by the participant during informal threshold estimation. Thus, sequence rate was held constant throughout the entire experimental session. Odd-numbered trials required tapping with the right hand (or the right hand led in the case of bimanual alternation), and even-numbered trials required tapping with the left hand (or the left hand led in bimanual alternation). In each trial, the participant began tapping with (synchronization) or after (syncopation) the third sequence tone. Instructions specified that the urge to drift from antiphase to in-phase should be resisted in syncopation conditions.

The task in the second experimental session differed from that in the first only with regard to the informal threshold estimation procedure and the rate at which sequences were subsequently presented. Whereas in the first session the just-manageable rate was estimated for unimanual syncopation, in the second session the participant was instructed to estimate his or her just-manageable rate for alternating bimanual syncopation (starting with the right hand). As was the case in the first session, sequence rate was held constant at this just-manageable value throughout the session.

Dependent measures

The main dependent measure is tap timing variability, which was indexed by calculating the variability of the asynchronies between the times at which taps should have occurred and the times at which they actually occurred. In addition, error rate, mean asynchrony, and drift were examined. Asynchronies were computed by subtracting the tone onset times (for synchronization) or the times corresponding to the midpoints between tones (for syncopation) from the tap onset times. (We were more interested in asynchronies than ITIs because the latter do not provide an index of how accurately taps are placed relative to the sequence.) Taps that missed their target—that is, a tone or the midpoint between tones—by more than ± 0.25 of the sequence IOI were identified and counted (along with omitted taps) as errors, which were excluded from the analyses of mean asynchrony and variability of asynchronies. The variability of asynchronies was measured by calculating coefficients of variation (CV); that is, the standard deviation of asynchronies from each condition was divided by the sequence IOI (which was different for most participants).[5] Error rates, mean asynchronies, and CVs of asynchronies were analyzed in separate Phase × Mode × Hand × Rate analyses of variance (ANOVAs). For the mode variable, two separate contrasts compared performance in the bimanual alternation conditions with performance in the unimanual and unimanual-skip conditions. Note that the hand variable refers to the identity of the hand that produced the asynchronies even for the bimanual alternation conditions. (Preliminary analyses revealed that whether the left or right hand was leading during bimanual alternation produced no significant effects, ps > .05.) Drift was indexed by measuring ITIs. Because target ITIs in the unimanual-skip conditions were twice as long as those in the standard unimanual and alternating bimanual conditions (which would produce trivial differences in comparisons of ITIs across these conditions), we calculated ITI difference scores by subtracting the target ITI value from the mean observed ITI from each condition. These ITI difference scores were analysed in a Phase × Mode × Hand × Rate ANOVA (with the hand variable referring to which hand led in the case of bimanual alternation).

Results

Participants' just-manageable rate estimates for alternating bimanual syncopation and unimanual syncopation are shown in Table 1. Here it can be seen that all participants selected slower rates for the former than for the latter, $t(7) = 6.42$, $p < .001$, providing evidence that participants subjectively felt that alternating bimanual syncopation is more challenging than unimanual syncopation. Error rates, mean asynchronies, and drift are considered briefly next, before the variability of asynchronies results are reported.

Errors

The percentage of errors data (omitted taps and asynchronies > $|\mathrm{IOI} \times 0.25|$) are shown in Figure 2. Note that these errors represent failures to maintain the prescribed phase relationship between taps and the pacing sequence. The Phase × Mode × Hand × Rate ANOVA revealed significant main effects of both phase and mode, indicating that more errors occurred (1) with syncopation than with synchronization, $F(1, 7) = 9.5$, $p < .02$, and (2) with bimanual alternation than with unimanual-skip tapping, $F(1, 7) = 12.2$, $p = .01$ (indeed, there were virtually no errors for the latter). There were also more errors for bimanual alternation than for standard unimanual tapping, but the difference only approached statistical significance,

[5] We did also examine CVs for ITIs, but these are not reported here as they display a pattern of results similar to that of CVs for asynchronies.

TABLE 1
Individual just-manageable rate estimates[a] for unimanual syncopation (fast) and alternating bimanual syncopation (slow)

Participant	*Unimanual*	*Bimanual*
P. K.	400	540
B. R.	420	520
A. M.	420	480
V. T.	460	560
R. F.	360	460
B. S.	380	500
B. W.	480	500
H. R.	480	640
M	425	525
SE	16	20

[a]In ms.

$F(1, 7) = 3.97, p < .1$. Although the main effect of rate also only approached significance, $F(1, 7) = 3.3, p > .1$, there was a significant interaction between phase and rate, $F(1, 7) = 14.2, p < .01$: The difference in the number of errors for syncopation (many) and synchronization (few) was greater at fast than at slow rates. In Figure 2 it can be seen that this Phase × Rate interaction does not apply in the case of unimanual-skip tapping: The three-way interaction between phase, mode (bimanual alternation vs. unimanual-skip), and rate is significant, $F(1, 7) = 8.6, p < .05$. The corresponding Phase × Mode (bimanual alternation vs. standard unimanual) × Rate interaction approaches significance, $F(1, 7) = 5.1, p = .058$, which makes it difficult to interpret. Finally, whether the left or right hand was tapping produced neither a significant main effect nor significant interactions with other variables.

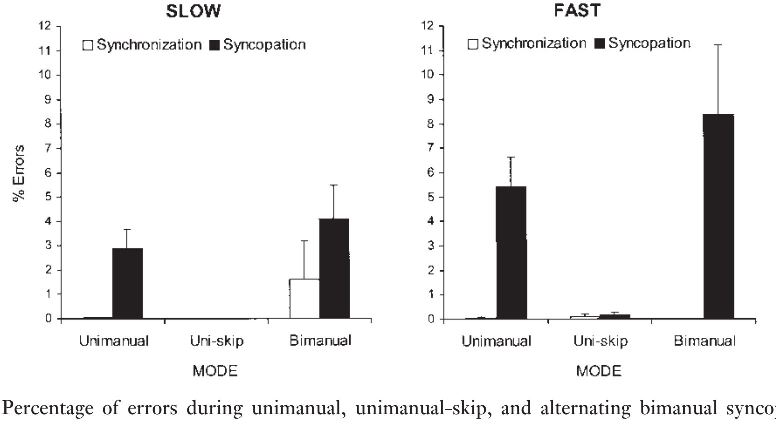

Figure 2. Percentage of errors during unimanual, unimanual-skip, and alternating bimanual syncopation and synchronization at slow and fast tempi, collapsed across the hand variable.

Mean asynchronies

Mean asynchronies reflect how early or how late taps occur on the average relative to their targets—that is, tones in synchronization and the midpoint between tones in syncopation. The usual tendency for taps to occur early—revealed in negative asynchronies (see Aschersleben, 2002)—was observed during synchronization at both slow and fast rates (–18 ms and –16 ms, respectively). However, a different pattern of results emerged for syncopation, where mean asynchrony was near zero at the slow rate (–2 ms) and positive at the fast rate (35 ms; cf. Fraisse & Ehrlich, 1955; Volman & Geuze, 2000). The reliability of the above differences in mean asynchrony was confirmed in the Phase × Mode × Hand × Rate ANOVA by significant main effects of both phase, $F(1, 7) = 13.6$, $p < .01$, and rate, $F(1, 7) = 8.8$, $p < .05$, and a significant interaction of these variables, $F(1, 7) = 5.7$, $p < .05$. There were no significant effects of mode or hand (ps > .05), indicating that mean asynchrony was not affected by how many or which of the hands tapped.

Drift

If people fail to maintain the correct tapping rate, the movement sequence drifts away from the pacing sequence. Drift was indexed here by ITI difference scores (i.e., observed minus target ITIs). Negative scores indicate that tapping rate was too fast (i.e., observed ITIs are shorter than target ITIs), and positive scores indicate that tapping was too slow (observed ITIs are longer than target ITIs). The ANOVA on ITI difference scores revealed main effects of both phase, $F(1, 7) = 14.97$, $p < .01$, and rate, $F(1, 7) = 12.2$, $p = .01$, and a significant Phase × Rate interaction, $F(1, 7) = 9.7$, $p < .02$. At slow rates, ITI difference scores were close to zero for both synchronization (–0.36 ms) and syncopation (0.38 ms), whereas at fast rates, the difference score for synchronization (–0.33 ms) remained close to zero but the syncopation difference score (4.45 ms) became a bit larger and positive. In any event, these values are all rather small, indicating that large-scale, monotonic drift did not occur. There were no significant effects of mode or hand.

Variability of asynchronies

The CVs of asynchronies data—which are informative about performance stability—are displayed in Figure 3. The Phase × Mode × Hand × Rate ANOVA yielded significant main effects of all four variables: CVs of asynchronies were higher for (1) syncopation than synchronization, $F(1, 7) = 14.3$, $p < .01$, (2) bimanual than either unimanual or unimanual-skip tapping, $F(1, 7) = 8.3$, $p < .05$, and $F(1, 7) = 12.0$, $p = .01$, respectively, (3) the left hand than the right hand, $F(1, 7) = 24.5$, $p < .01$, and (4) fast rates than slow rates, $F(1, 7) = 13.8$, $p < .01$. Finding that variability in asynchronies is greater for syncopation than for synchronization is not surprising, and the result that variability was greater at fast rates than at slow rates is mainly due to performance during syncopation, as evidenced by a significant Phase × Rate interaction, $F(1, 7) = 10.0$, $p < .02$. The finding that bimanual alternation was more variable than unimanual or unimanual-skip tapping is noteworthy, as it points to general costs associated with the use of two alternating hands (cf. Wing et al., 1989). The finding that variability was higher in the nonpreferred hand is also notable, as is the significant interaction between hand and rate, $F(1, 7) = 24.4$, $p < .01$, indicating that the nonpreferred hand was especially

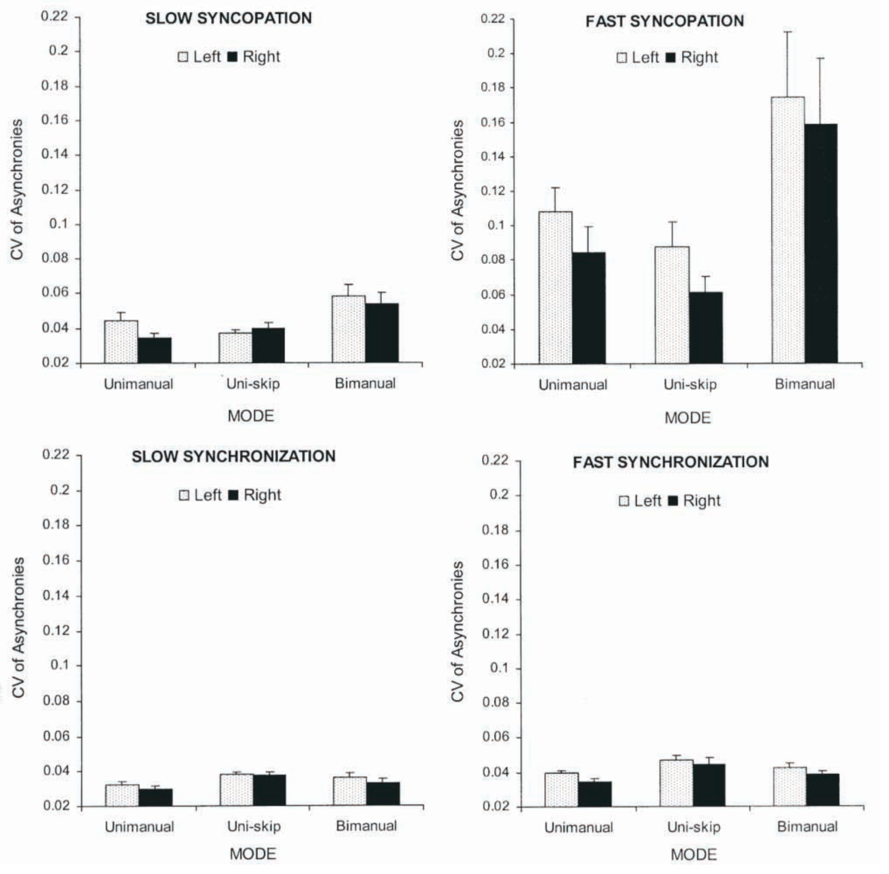

Figure 3. Coefficients of variation (CVs) representing normalized variability of asynchronies for the left and right hands during unimanual, unimanual-skip, and alternating bimanual syncopation (top row) and synchronization (bottom row) at slow (left column) and fast rates (right column).

variable at fast rates (cf. Truman & Hammond, 1990, who found no such effect in a unimanual synchronization–continuation task). Some further interactions between the above effects shed light on the specific issue of how alternating bimanual syncopation relates to the other coordination modes.

A significant Mode × Phase interaction—for both the bimanual/unimanual contrast, $F(1, 7) = 6.5$, $p < .05$, and the bimanual/unimanual-skip contrast, $F(1, 7) = 17.5$, $p < .01$—indicates that the differences in variability between bimanual alternation and unimanual tapping were amplified during syncopation relative to synchronization. It is noteworthy that alternating bimanual synchronization was actually less variable than unimanual-skip synchronization, whereas bimanual syncopation was much more variable than unimanual-skip syncopation. This interaction effect was more pronounced at fast than at slow rates, $F(1, 7) = 5.9$, $p < .05$, probably because syncopation is more sensitive to rate manipulation. The decrease in variability from unimanual-skip synchronization to alternating bimanual synchronization—although itself not significant, $t(7) = 1.76$, $p = .12$—is consistent with the notion of a single timekeeper that experiences a reduction in period (hence less variability) when going from the unimanual-skip to the bimanual alternation condition. Semjen and Summers (2002) offer a similar interpretation in the context of a 2:1 bimanual tapping study (i.e., one hand taps at twice the frequency of the other) where they found that the slower hand of the 2:1 pair is less variable than when it performs its task alone (also see Walter, Corcos, & Swinnen, 1998). Our finding of a difference between synchronization and syncopation, when viewed in this light, may suggest different primary sources of variability: movement frequency for synchronization and the extra level of antiphase coordination for syncopation. In any case, the requirement to use two alternating hands increased the variability of asynchronies relative to standard unimanual tapping, and it did more such damage during syncopation than during synchronization.

Finally, we consider the effects of using the nonpreferred hand during alternating bimanual syncopation. A significant Phase × Hand interaction, $F(1, 7) = 23.7$, $p < .01$, indicates that the difference in variability between the left and right hands was generally larger during syncopation than during synchronization. This effect was more evident at fast than at slow rates, $F(1, 7) = 12.1$, $p = .01$, suggesting that the nonpreferred hand was not only more sensitive to the rate manipulation (i.e., the Hand × Rate interaction mentioned earlier), but also that its sensitivity was heightened during syncopation. Importantly, however, there were no significant interactions involving mode and hand (ps > .2), which suggests that the nonpreferred hand did not affect performance differently in alternating bimanual syncopation than in alternating bimanual synchronization and the various unimanual conditions. In other words, although the nonpreferred hand is generally problematic during syncopation, it does not seem to play a special role in augmenting the variability of asynchronies during alternating bimanual syncopation.

Discussion

In this study we investigated alternating bimanual syncopation, a coordination mode in which the left and right hands move in alternation to produce finger taps in antiphase with an auditory metronome. Our primary aim was to determine whether alternating bimanual syncopation is more difficult than standard unimanual syncopation (i.e., antiphase tapping with the preferred hand). A secondary aim was to assess how factors such as the involvement of the nonpreferred hand, the movement frequency of each hand, and the extra level of antiphase coordination (introduced by the requirement to use two alternating hands) contribute to the (in)stability of alternating bimanual syncopation. The variability of asynchronies was used as an index of performance stability. Errors (taps that were omitted or missed their target by 0.25 of the IOI), mean asynchronies, and drift were also examined, but—as they did not differentiate between alternating bimanual syncopation and unimanual syncopation—these measures add little to the story told by the variability measure and hence will not feature further in this discussion.

Variability in asynchronies was compared across conditions that required alternating bimanual syncopation, unimanual syncopation (with the left or right hand), unimanual-skip syncopation, wherein taps were made after every other tone (with the left or the right hand), and the three corresponding synchronization modes at fast and slow rates. Asynchronies were found to be more variable with an alternating hand assignment than with standard unimanual tapping for both syncopation and synchronization, and moreover this bimanual disadvantage was more pronounced during syncopation than during synchronization. Indeed, alternating bimanual syncopation proved to be by far the most unstable coordination mode. Furthermore, tap timing variability was lower for unimanual-skip than alternating bimanual tapping in the case of syncopation, but not for synchronization (where variability was actually slightly higher in unimanual-skip than alternating bimanual conditions). This suggests that whereas the lower movement frequency in each hand can account fully for the increase in variability from standard unimanual to alternating bimanual synchronization, it certainly cannot do so in the case of syncopation, where the lower movement frequency in each hand actually seems to enable more stable performance. Finally, although variability was generally greater for the nonpreferred hand than for the preferred hand (and especially during syncopation at fast rates), there was no indication that the use of the nonpreferred hand affected performance differently in alternating bimanual syncopation than in the other coordination modes. Taken together, the above findings suggest that neither movement frequency nor dexterity limits of the nonpreferred hand holds primary responsibility for the augmented variability observed in alternating bimanual syncopation. Therefore, it seems that the extra level of antiphase coordination imposed by the requirement to use two alternating hands is the most potent contributor to instability during alternating bimanual syncopation. There are several possible reasons why this may be the case.

If alternating bimanual syncopation comprises two coupling collectives—metronome–hand and hand–hand—then it can be viewed as residing within a dynamical state space with multiple attractors: both an antiphase and an in-phase attractor in the metronome–hand (perception–action) collective, and an antiphase and in-phase attractor in the hand–hand (action–action) collective. Byblow et al. (1995) have shown in a study that pitted various coordination modes against one another (albeit in a manner different from that of the current study) that, other things being equal, perception–action coupling is weaker than action–action coupling, and antiphase attractors are weaker than in-phase attractors. Thus, there are asymmetries both between and within the two collectives involved in alternating bimanual syncopation, which is suggestive of an uneven dynamical landscape in which competition between attractors may heighten overall instability, thereby increasing the potential for phase drift. Similar theoretical themes can be found in work concerned with spatial constraints on rhythmic coupling (Chua & Weeks, 1997; Wimmers, Beek, & van Wieringen, 1992).

Although the results of the current study clearly demonstrate that alternating bimanual syncopation is relatively unstable, the data obtained are not ideal for investigating phase transitions as (1) rates were not fast enough to induce failures within the action–action collective (i.e., hand alternation devolving to unison tapping), and (2) participants occasionally omitted taps to avoid tapping in-phase with the metronome (probably due to the instructions to resist drift). To map the asymmetries in the dynamical state space of alternating bimanual syncopation, it would be useful in future work to conduct a phase transition study that tests performance at a wider range of rates with instructions not to resist drift. To the extent that the findings of Byblow et al. (1995) generalize to alternating bimanual syncopation, it would be expected that perception–action coupling should be the first to give way, with the alternating hands drifting to an in-phase relationship with the metronome, followed by demise of antiphase action coupling, resulting in the hands themselves drifting to an in-phase relationship. It also might be the case that the nonpreferred hand makes a greater contribution than the preferred hand to phase transitions. Coupling asymmetries could also be studied further by comparing our current version of alternating bimanual syncopation with a version that requires the alternating movements to be made with two adjacent fingers on one hand, a task that should be even more challenging (for a similar manipulation, see Summers, Bell, & Burns, 1989). The asymmetries in coupling strength between the perception–action and action–action collectives in this single-hand version of the task should be heightened relative to the bimanual version, as coupling between adjacent fingers is presumably stronger than coupling between the two hands.

Another possible explanation for the difficulty of alternating bimanual syncopation invokes the concept of attentional resource allocation. Indeed, attention has been postulated to play a role in other bimanual coordination tasks: For example, Peters (1985) found that performance suffered when attention was focused on the nonpreferred hand during bimanual dual tasks, such as tapping a simple rhythm with one hand while simultaneously tapping as fast as possible with the other hand. Alternating bimanual syncopation, too, can be viewed as a dual task wherein both components—the maintenance of an antiphase relationship with the metronome (in the perception–action collective) and the alternating hand assignment of responses (in the action–action collective)—require attention. When carried out concurrently, the requirement to alternate hands may divert attentional resources from the task of maintaining antiphase with the metronome (which is already demanding when carried out alone), thereby leading to performance decrements within the perception–action collective. Specifically, such diversion of attention may weaken perception–action coupling (see Large & Jones, 1999, for a theory addressing the relationship between attention and such coupling), in effect augmenting the preexisting asymmetry in coupling strength between the perception–action and action–action collectives (see Byblow et al., 1995).

A strong version of this hypothesis states that the commandeering of attention by the action–action collective is problematic because it shifts the primary focus of the dual task from the perception–action collective to the action–action collective. Specifically, the requirements of alternating bimanual syncopation may preclude the optimal allocation of attention across these collectives by changing the locus of the *referent periodicity* that guides movement timing. There is considerable evidence that temporal pattern perception and production are subserved by hierarchical timekeeper mechanisms comprising an internal referent periodic process (which plays a dominant role in temporal organization and is often reflected in foot tapping while performing or listening to music), as well as superordinate and/or subordinate periodicities that group or subdivide the referent period, respectively (see Drake, Jones, & Baruch, 2000; Large & Jones, 1999; Pressing, 1999; Vorberg & Wing, 1996). In standard unimanual syncopation, an internal periodicity aligned with the metronome—which is invariant and beyond control—serves as a referent that is subdivided by a second (more variable and mutable) periodicity supporting the taps. Thus, behaviour is organized around a stable externally based referent. The requirements of alternating bimanual syncopation may upset this balance by drawing attention to the hands, thereby producing a situation in which the periodicity underlying the taps functions as the referent, and the metronome-based periodicity serves as the subdivision. This substitution of a stable externally based referent with a relatively unstable internal referent would presumably interfere with antiphase coordination, as it conflicts with a compelling tendency for attention to become entrained to periodicities in the environment (Large & Jones, 1999).

A final issue that warrants investigation is the degree to which the problems associated with alternating bimanual syncopation can be overcome. For instance, is there less disparity between the stability of alternating bimanual syncopation and standard unimanual syncopation for musicians who specialize in the production of complex bimanual rhythms (e.g., professional percussionists) than for other musicians, or does the relative difficulty of alternating bimanual syncopation remain unaffected by such experience? The effects of feedback are also relevant: Performance stability might be improved by the addition of auditory feedback, such that a tap by each hand triggers a tone of unique pitch, which is also different in pitch from the pacing tones. Indeed, there is considerable evidence that directing attention to action effects (i.e., focusing on the consequences of one's actions in the external environment) is more beneficial than directing attention to action production itself (i.e., focusing internally on motor processes) in contexts ranging from bimanual circle drawing to sport (e.g., Mechsner et al., 2001; Wulf & Prinz, 2001). Focusing on feedback tones during alternating bimanual syncopation would effectively change the goal of the task from one where the performer aims to generate two levels of antiphase movement, to one where the aim is simply to produce a coherent sequence of alternating tones, much like the arpeggiated figures that often accompany the melody in classical music. Under such a strategy, action is guided by a control structure located exclusively within the perceptual domain, rather than by a structure spanning perceptual and motor domains. This "disembodied" locus of control may reduce instability in alternating bimanual syncopation by (1) lessening the impact of coupling constraints that implicate the motor system, and/or (2) discouraging the disproportionate allocation of attention to the alternating hands. Both of these remedies have in common the potential to redress the asymmetry between perception–action and action–action collectives that appears to be problematic during alternating bimanual syncopation.

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