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The influence of perceptual and motor factors on bimanual coordination in a polyrhythmic tapping task

Jeffery J. Summers, Jennifer A. Todd, and Young H. Kim

Department of Psychology, University of Melbourne, Parkville, Victoria, Australia, 3052

Summary. In this study the role of perceptual and motor factors on the motor organization (integrated versus parallel) adopted by musically skilled and unskilled subjects in a polyrhythmic tapping task was investigated. Subjects tapped a 3:2 polyrhythm to match the timing of two isochronous tone trains, one tone train for each hand. Perceptual factors were examined by the manipulation of the frequency difference between the tone trains to produce either an integrated or a streamed percept. Motor factors were examined by comparison of performance on two versions of the 3:2 polyrhythm. In one (simultaneous) version, each cycle of the polyrhythm began with a simultaneous left- and right-hand tap. In the other (shifted) version a 100-ms interval was introduced between the initial left and right taps in each cycle. Examination of the pattern of variances and covariances among intertap intervals suggested that most of the subjects in this study adopted an integrated motor organization that involved interleaving the timing of the two hands. Further analysis revealed that a serial chained model described the pattern of covariances best for the simultaneous pattern, whereas a hierarchical organization described the pattern of covariances for the shifted pattern best. The finding that performance was more accurate with integrated tones than with streamed tones provides some support for a perceptual-motor facilitation hypothesis.

Introduction

When people are required to produce two differently timed motor sequences at the same time, such as tapping five regular beats with one hand and three regular beats with the other hand, mutual interference is commonly observed. The form and locus of these interference effects, and how they are overcome, are important issues in research on bimanual coordination.

There appear to be two possible ways in which the constraints on bimanual movement can be overcome to allow individuals concurrently to perform temporally incompatible motor sequences, such as polyrhythms. One possibility is that practice results in the development of independent timing mechanisms for each hand, so that they operate in parallel. Shaffer (1981), for example, concluded from a detailed examination of the rhythmic interplay between the hands of highly skilled pianists that they are able to time independently the movements of the two hands. An alternative solution to the dual-task problem is to combine the separate activities into a new higher-order activity. In this way the performer does not have to control each hand separately. Deutsch (1983), for example, has argued that the ability to generate concurrently two isochronous sequences reflects the development of a representation of the patterns as an integrated whole. Consistent with this view was the finding that the accuracy of performance of polyrhythmic sequences of musically trained subjects was inversely related to the complexity of the associated integrated representation.

A more direct test of parallel (independent control over the hands) and integrated (interleaving the movements of the hands) motor organizations in a polyrhythmic tapping task was carried out by Jagacinski, Marshburn, Klapp, and Jones (1988). They attempted to distinguish not only between parallel and integrated organizations, but also between chained and hierarchical models of motor-timing patterns (see Figure 1). The analysis of tapping data was based on a model of the timing of repetitive movements developed by Wing and Kristofferson (1973) and extended to the bimanual situation by Vorberg and Hambuch (1978, 1984). The model assumes two processes that operate in the timing of intertap intervals: (a) a central timekeeper generating a series of internal events, each of which initiates a motor response; and (b) an implementation process that introduces motoric delays in the execution of responses. Each process is assumed to operate as a series of

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Correspondence to: J. J. Summers, who is now at the Department of Psychology, University of Southern Queensland, Post Office Darling Heights, Toowoomba, Queensland, Australia 4350

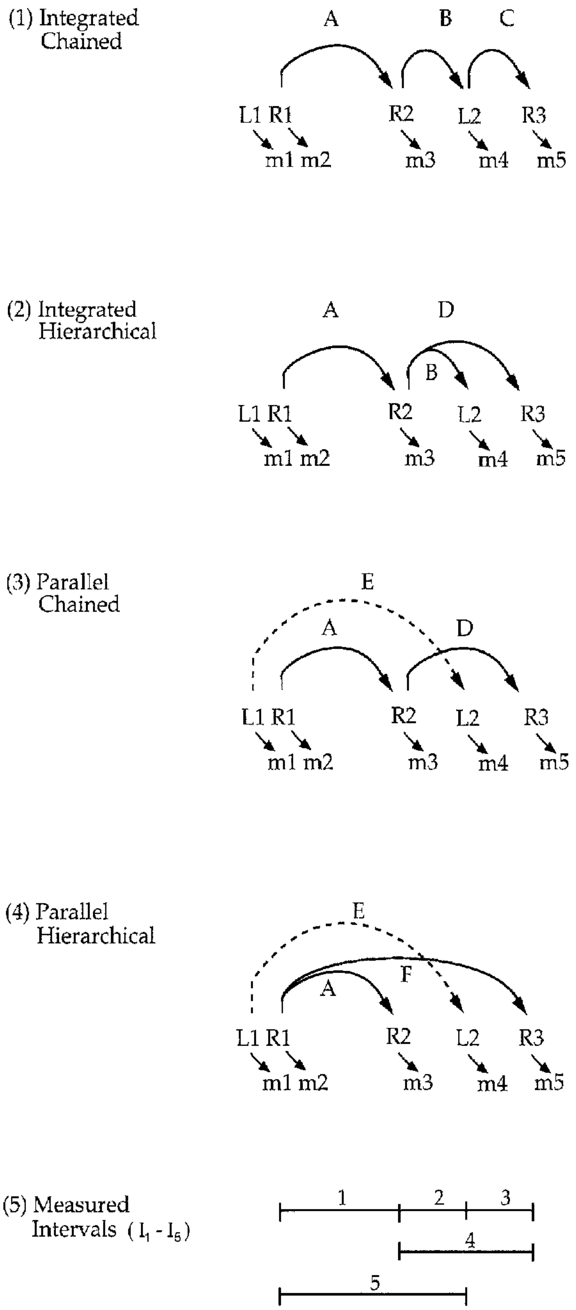

Fig. 1. Integrated and parallel models of motor organization (adapted from Jagacinski et al., 1988). See text for details

independent, randomly varying, intervals. Figure 1 shows four of the six motor organizations examined by Jagacinski et al. (1988) for a 3:2 polyrhythm: L1, R1, etc., represent internal events corresponding to taps with the left and right hands respectively; A–F represent the timekeeper intervals, and m1–m5 the motor delays. The actually observable intertap intervals (measured intervals I_1–I_5 in Figure 1) therefore reflect both timekeeper and motor-delay processes.

In Figure 1 chained and hierarchical organizations are shown for both integrated and parallel models. In an integrated, chained organization the two hands operate on a common time base and each response is cued by the previous response in the sequence, irrespective of hand. A hierarchical organization, in contrast, involves higher-order units, with lower-order units being triggered by higher-order ones, but not vice versa. For example, in the integrated hierarchical model shown in Figure 1, the internal event R2 triggers both the higher-order interval D and the lower-order interval B. Jagacinski et al. (1988) also distinguished between two forms of hierarchical organization: an independent hierarchical organization in which intervals B and D are independent of each other and a multiplicative hierarchical organization in which B is ratio-related to D. Similar organizations were tested for parallel models in which separate timekeepers were assumed for each hand (see Figure 1).

Jagacinski et al. (1988) used patterns of variance and covariance among intertap intervals to distinguish between integrated and parallel models in the performance of a 3:2 polyrhythm by eight experienced piano players. An integrated motor organization was indicated for all subjects. Furthermore, a regression analysis performed on the variance–covariance predictions for each integrated model showed that the multiplicative hierarchical model provided the best fit to the data. In more recent studies it has also been found that an integrated, rather than a parallel, organization is used by both skilled (musically trained) and unskilled subjects in a polyrhythmic tapping task (Peters & Schwartz, 1989; Summers, Rosenbaum, Burns, & Ford, in press). In particular, a form of hierarchical, integrated organization, in which movements of the slow hand are subordinate to movements of the fast hand, has been commonly observed. Furthermore, neither extensive practice (Summers, Ford, & Todd, in press) nor learning the motor pattern for each hand separately before combining them (Klapp, Martin, McMillan, & Brock, 1987; Summers & Kennedy, 1992) induced the development of a parallel organization.

In general, the research to date does not support the view that successful performance of polyrhythmic sequences involves the utilization of independent timing mechanisms for each hand. It is possible, however, that the way the polyrhythms were presented to subjects in these studies encouraged the adoption of an integrated organization. Typically, polyrhythmic sequences are presented as two isochronous tone trains, one tone train for each hand sequence. Subjects learned the polyrhythm by tapping the left hand in synchrony with one tone train and the right hand in synchrony with the other train. In most studies of polyrhythmic tapping the two tone trains have been relatively close in pitch. Previous research has shown, however, that the manipulation of the frequency difference between tone trains can exert a strong influence on the perceptual organization reported (Bregman & Campbell, 1971). When the pitch difference between tone trains is small, the tones are perceived as forming a serially integrated pattern. Large differences between tone trains, in contrast, produce a streamed percept in which two independent parallel streams of tones are perceived. The lack of evidence for a parallel organization in polyrhythmic tapping may therefore be due to perceptual, rather than to motor, factors. That is, streamed and integrated tone sequences may induce different motor organizations. Jagacinski et al. (1988) referred to this hypothesis as the *perceptual-dominance hypothesis*. They found, however, that even when the tones were perceptually streamed, musically trained subjects adopted an integrated-response structure in the production of a 3:2 polyrhythm. The fact that performance with streamed tones was less accurate than with integrated tones, however, provided some support for a *perceptual-motor-facilitation hypothesis*. That is, performance was facilitated when the perceptual organization was isomorphic with the motor organization adopted (i.e., when both were integrated).

Another factor that may have influenced the adoption of an integrated motor organization by subjects in previous experiments is the requirement that each cycle of a polyrhythm should be initiated with a simultaneous right- and left-hand tap (see Figure 1). There is some evidence to suggest that the independent operation of the limbs may be easier to achieve if the initiation of one movement is delayed with reference to the other. Swinnen, Walter, and Shapiro (1988) examined subjects' ability to make simultaneous upper-limb movements that differed in their spatiotemporal requirements. Over the course of a long practice session some subjects were able to achieve complete independence between the limbs, while for other subjects the limbs became more coupled. The degree of limb independence observed appeared to be related to the absolute time differences between the initiation of the two limb movements. The more the initiation of one movement was delayed in relation to the other, the more the limb movements appeared to be uncoupled. It is possible, therefore, that the introduction of a delay between left- and right-hand taps at the start of each cycle in a polyrhythmic tapping task may facilitate the use of a parallel motor organization. This manipulation was, in fact, attempted by Jagacinski et al. (1988). Subjects received extensive practice on a 3:2 polyrhythm in which each cycle was initiated by simultaneous left- and right-hand taps before being tested on a pattern in which the three right-hand taps were shifted 108 ms later in the cycle. Although the shifting of the pattern produced a marked decrement in performance, the variance–covariance patterns indicated that an integrated organization was being used by most subjects. It may be, however, that the earlier practice on the normal version of the 3:2 pattern with an integrated organization influenced the organizational strategy adopted by subjects in the shifted pattern.

There is some evidence, therefore, that perceptual factors (streamed vs. integrated tones) and motor factors (initiation delay) exert a strong influence on the accuracy of polyrhythm production, but not on the underlying motor organization. The aim of the present research was to investigate these factors in more detail through a replication and extension of the Jagacinski et al. (1988) study. As in this earlier study, we examined the effect of perceptual streaming on the motor organization adopted in the performance of two versions of a 3:2 polyrhythm. In order to control for previous practice effects, however, the subjects in our study were trained either on the normal 3:2 polyrhythm (a two-handed tap at beginning of each cycle) before they transferred to the shifted pattern or were trained on the shifted pattern before transfer to the normal 3:2 pattern.

It was hypothesized that subjects who adopted a parallel motor organization would perform better on the transfer task than subjects who adopted an integrated motor organization. An integrated strategy would require the learning of a new complex integrated pattern for the transfer task. A parallel strategy, in contrast, by decomposing the training pattern into two simpler parts (i.e., tapping three regular beats and two regular beats) would not only result in a less complex internal representation but also be easily generalizable to the transfer pattern (Jagacinski et al., 1988). We also compared the performance of musicians and nonmusicians, as Shaffer's (1981) studies of pianists suggest that a parallel motor organization would most likely be observed in subjects who had previous musical experience.

In line with previous research, it was predicted that interleaving the timing of the two hands would be the dominant motor organization adopted by subjects in this experiment. Of particular interest, however, was whether independence between the hands would be observed when subjects were given extensive practice on a task in which the perceptual–motor correspondence encouraged the adoption of a parallel motor organization (i.e., streamed tones, shifted pattern).

Method

Subjects. Forty-eight right handed subjects from the University of Melbourne participated in the experiment. Of these, 24 were experienced musicians, having played the piano for at least six years and 24 were nonmusicians without any previous training. Each subject participated in three sessions held on consecutive days.

Apparatus and tasks. Subjects were required to tap out repetitively a 3:2 polyrhythm on two keys (Honeywell Microswitch PK89 133), using the index fingers, with the right hand taking the faster beat. The polyrhythm was presented to subjects, through headphones, as two parallel trains of 30-ms sine wave tones. Each cycle of the polyrhythm was 1,300 ms in duration, producing a 433-ms onset-to-onset interval for the three-beat tone pattern and a 650-ms onset-to-onset interval for the two-beat tone pattern. The first beat of the two-beat pattern (L1, Figure 2) was accented, to indicate the beginning of each cycle of the 3:2 polyrhythm. To produce a perceptually streamed pattern, the frequencies of the two tone trains were 433 Hz and 3130 Hz, respectively. A perceptually integrated pattern was produced by tone frequencies of 794 Hz and 1163 Hz. The assignment of high or low tones to the left and right ears was counterbalanced within groups of subjects.

There were two versions of the 3:2 polyrhythm: (a) a pattern in which each successive cycle began with a simultaneous right-hand and left-hand response, the *simultaneous* pattern (Figure 2, top); (b) a pattern in which each successive cycle began with a left-hand response because the three-beat right-hand pattern was shifted 100 ms later in the cycle than the two-beat left-hand pattern, the *shifted* pattern (Figure 2, bottom). It should be noted that shifting the right-hand pattern in relation to the left-hand pattern changed the time relations between hands, but not within a hand. Half the subjects (12 musicians and 12 non-musicians) were trained on the simultaneous pattern and then transferred to the shifted pattern, and half trained on the shifted pattern before being transferred to the simultaneous pattern.

Two different response tasks were used during the experiment. In the *synchronization* task subjects were instructed to tap with the right index finger in synchrony with the tones delivered to the right ear, and with the left index finger in synchrony with the tones delivered to the left ear. Each trial consisted of 32 cycles of the polyrhythm. In the *continuation* task, after an initial period of synchronization (two cycles of a rhythm), the stimulus tones stopped and the subject attempted to continue tapping

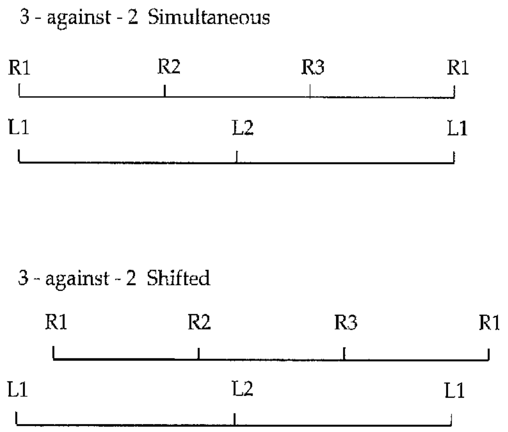

Fig. 2. Schema of the temporal relationships between the two hands required in the performance of the simultaneous and shifted patterns (one cycle of each repeating pattern is shown). Each vertical line represents a tap with either the right (R) or left hand (L)

the rhythm, at the same tempo, for an additional 30 cycles. Auditory-feedback tones of the same loudness and frequency as those of the stimulus tones were presented with each keytap in the continuation phase.

Immediately before the start of each trial in the synchronization and continuation tasks, the subject was shown a diagram of the temporal relationships between the two hands required in the performance of the rhythm (see Figure 2). Subjects were also allowed to listen for as long as they wished to the pacing tones before tapping on the keys. For half the subjects (6 musicians, 6 non-musicians) in each training/transfer combination (e. g., simultaneous/shifted), the tone sequences produced a streamed percept; and for the other half, the tones produced an integrated percept. Performance feedback, in terms of mean intertap interval (ITI) and standard deviation (*SD*) for each interval in a cycle, was provided at the end of each trial.

Procedure. The first session was a training day aimed at teaching subjects a particular rhythm and giving practice in the two response tasks. So that subjects should be familiarized with the apparatus and tasks, they first performed simultaneous and shifted versions of the simple rhythms 2 : 1 (650 ms, 1,300 ms) and 3 : 1 (433 ms, 1,300 ms) using the synchrony task.

After these trials subjects were introduced to the version of the 3 : 2 polyrhythm they were to perform throughout training, i. e., the simultaneous or the shifted pattern. Subjects were first given 10 trials of the pattern with a cycle duration of 1,800 ms (600 ms, 900 ms), 5 trials of synchrony, and 5 of continuation. The subjects then began training on the pattern at the faster (1,300-ms) rate. The training phase consisted of an alternating series of 5 trials in the synchronization task followed by 5 trials in the continuation task. A total of 10 trials (320 cycles) was completed in each response task.

On Day 2, subjects continued to practice on the pattern (i. e., simultaneous or shifted) to which they had been assigned. The training session consisted of 5 trials (160 cycles) in the synchrony task followed by 20 trials (640 cycles) in the continuation task.

The first part of Day 3 was devoted to continued practice on the pattern and consisted of 10 trials in the continuation task. The ability of subjects to transfer to the other version (simultaneous or shifted) of the 3 : 2 polyrhythm was then examined. The transfer phase consisted of 5 trials of synchrony, followed by 10 trials of continuation on the new pattern.

Data analysis. Each training and transfer trial consisted of 32 cycles of the polyrhythm. The first two repetitions, however, were regarded as practice and were excluded from data analysis. Furthermore, only correct response cycles were analyzed. A response cycle was deemed correct if (a) the responses occurred in the correct order, irrespective of timing and (b) in the simultaneous pattern, the simultaneous response at the beginning of each cycle was made with less than 20 ms separating the right- and left-hand taps.

Table 1. Covariance predictions for the six models of motor organization

Model	Cov (I_1, I_3)	Cov (I_4, I_5)
INTEGRATED		
Chained	0	Var B
Independent hierarchical	0	0
Multiplicative hierarchical	0	$\bar{P}$Var D
PARALLEL		
Chained	Var A	0
Independent hierarchical	0	0
Multiplicative hierarchical	$\bar{Q}$Var F	0

Results

Of particular interest in this study were the effects of the manipulation of perceptual (streaming) and motor (initiation-delay) factors on the motor organization adopted by skilled and unskilled subjects in the performance of a 3 : 2 polyrhythm. To examine this question we followed the procedure used by Jagacinski et al. (1988). The first stage of analysis involved covariance analyses to distinguish, generally, between integrated and parallel modes of coordinating the two hands. In the second stage regression analyses were used to distinguish between specific models of motor organization.

Integrated vs. parallel motor organization

Covariance analyses. In accordance with Jagacinski et al. (1988), the five intertap intervals (I) shown at the bottom of Figure 1 were described in terms of timekeeper and motor delays for three versions (chained, independent-hierarchical, multiplicative-hierarchical) of both the integrated and the parallel models. In the integrated independent hierarchical model, for example, $I_1 = A + m3 - m2$ and $I_3 = D - B + m5 - m4$. For the simultaneous pattern, variance-covariance predictions were generated for each model, based on the five intertap intervals, so that in total there were 15 predictions for each model (see Appendix). Intervals were selected where the integrated models made qualitatively different covariance predictions to the parallel models.

As is shown in Table 1, these intervals were (I_1, I_3) for which all three integrated models predict zero covariance; two of the parallel models predict positive covariances; intervals I_4, I_5, for which all three parallel models predict zero covariance, and two of the integrated models predict positive covariances. In both sets of models, the independent hierarchical organization predicts zero covariance for intervals (I_1, I_3) and (I_4, I_5). For the shifted pattern an additional independent timekeeper between L1 and R1 was introduced into the models. This modification, however, did not alter the covariance predictions for the relevant intervals.

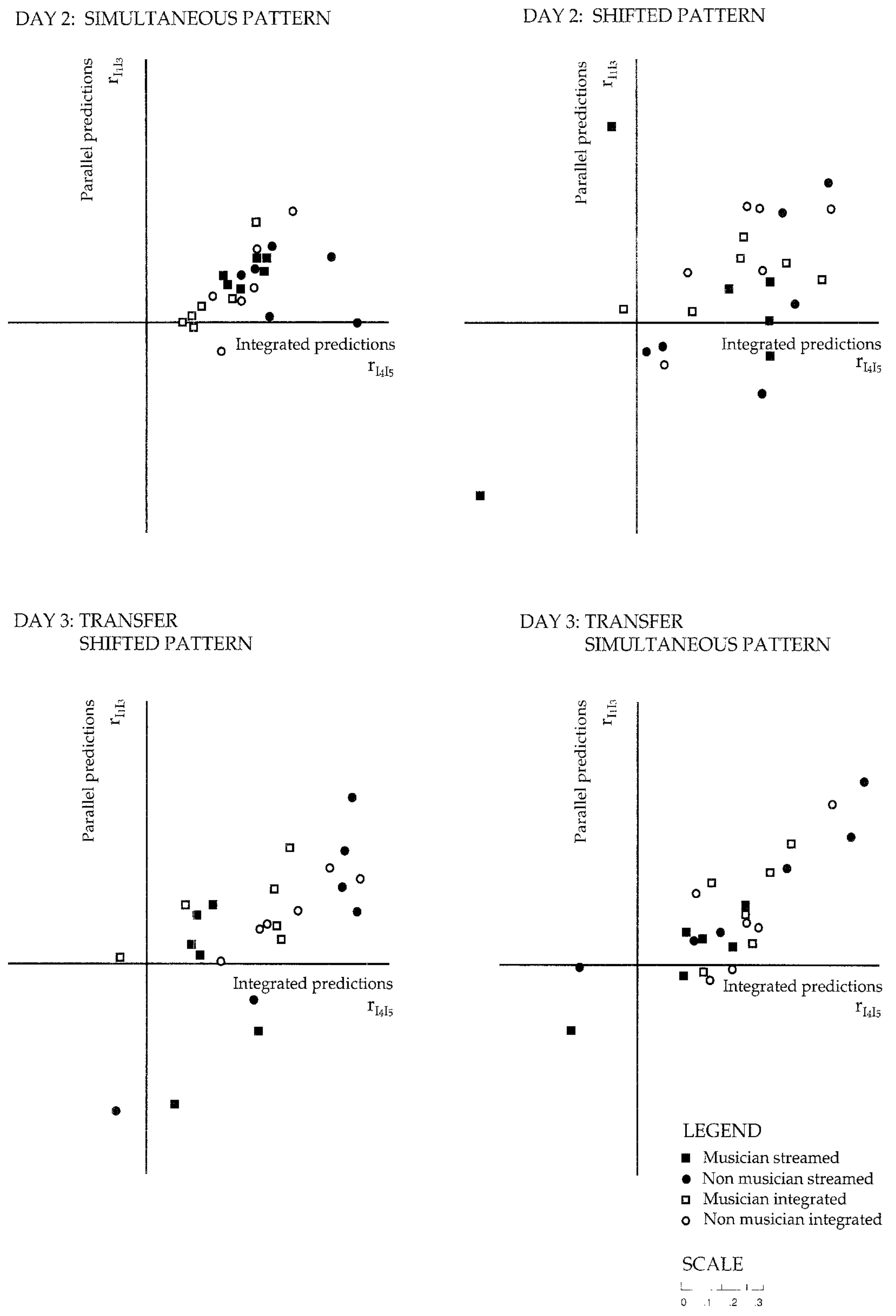

Fig. 3. Crossplots of correlations of intertap intervals on Day 2 (training) and Day 3 (transfer) for individual subjects. Correlations consistent with an integrated motor organization would lie along the positive horizontal axis. Correlations consistent with a parallel motor organization would lie along the positive vertical axis

To test whether subjects used an integrated or a parallel organization during the training phase of the experiment, variances and covariances were calculated on the continuation-task data for each subject over the last 15 trials on Day 2. The maximum number of correct response cycles was 450 – i.e., 15 trials × (32–2) cycles per trial. For the simultaneous pattern the number of correct cycles analyzed across the 24 subjects ranged from 184 to 450, and for the 24 subjects producing the shifted pattern the range was from 203 to 450 cycles. The covariances of intervals (I_1, I_3)

Table 2. Number of subjects for whom each integrated model accounted for the largest proportion of variance

	Chained	Independent hierarchical	Multiplicative hierarchical
TRAINING – DAY 2			
Simultaneous pattern			
Integrated tones	7	3	1
Streamed tones	7	2	2
Shifted pattern			
Integrated tones	3	4	4
Streamed tones	3	3	1

and intervals (I_4, I_5), converted to correlations for ease of plotting, are shown in Figure 3 for the simultaneous and shifted patterns. Because of the large sample sizes, correlations larger than about .15 are statistically significant. Correlations consistent with an integrated organization ($r_{I1,I3} = 0$) would lie along the positive horizontal axis of the graph, whereas correlations consistent with a parallel organization ($r_{I4,I5} = 0$) would lie along the positive vertical axis.

For the simultaneous pattern (Figure 3, Day 2) the data, in general, lie closer to the horizontal than to the vertical axis, suggesting the use of some form of integrated organization by most, if not all, subjects. Although the data for the shifted pattern (Figure 3, Day 2) are much more variable, the distribution of correlations is also more consistent with an integrated than with a parallel organization. Furthermore, for both patterns the data appear similar for musicians and for non-musicians, and for streamed and for integrated tone conditions. Perhaps the most striking feature of these data is that there do not appear to be any clearcut instances of a parallel organization among the 48 subjects tested.

The correlations for the transfer trials (Day 3) are also shown in Figure 3. During these trials, subjects trained on the simultaneous pattern transferred to the shifted pattern and vice versa. These data are based on the 10 transfer trials performed in the continuation task. Thus, the maximum number of correct response cycles was 300, – i.e. 10 trials × (32–2) cycles per trial. The number of correct cycles ranged from 84 to 300 for the simultaneous pattern, and from 114 to 300 for the shifted pattern. Although the transfer data are more variable than the training data, the distribution of correlations for both patterns suggests that an integrated organization was used by most of the subjects. As with the training data, the adoption of an integrated organization appeared uninfluenced by musical training or perceptual streaming.

Distinguishing between integrated models

Regression analyses. As there was little evidence in the previous analyses for the use of a parallel organization, the regression analyses were restricted to distinguishing between the three integrated models: chained, independent-hierarchical, and multiplicative-hierarchical. Following Jagacinski et al. (1988), a least-squares fit to the 5 variances and 10 covariances for the intervals $I_1 - I_5$ predicted by each model was obtained. For example, in the independent hierarchical model (see Appendix), the variances and covariances of the intervals I_1 to I_5 are all linear functions of four variables, Var A, Var B, Var D, and Var M. If we consider each variance and covariance as a value Y, and each coefficient associated with the variables, Var A to Var M, as values X1 to X4, we can match each Y value (variance or covariance) with a particular vector of coefficients X1 to X4. So for the Y value equal to Var (I_2) the associated vector of coefficients is (0,1,0,2). The variables Var A etc. then may be compared to the beta weights in a multiple-regression problem with the intercept set at zero. A similar procedure can be used for the other models (see Jagacinski et al., 1988, for further details). The modeling was carried out on the continuation-task data for the last 15 training trials on Day 2.

Table 2 shows the number of subjects for whom each integrated model provided the best least-squares fit with positive-variance estimates.[1] Two subjects performing the simultaneous pattern and 6 performing the shifted pattern could not be classified, as all three models gave negative variance estimates, and hence were uninterpretable. Of the 22 subjects classified in the simultaneous pattern, the chained model was superior for 14 (64%) subjects, the independent hierarchical model was superior for 5 subjects, and the multiplicative hierarchical model was superior for 3 subjects. In contrast, for the shifted pattern the chained model accounted for the greatest proportion of variance in the variance–covariance measures for only 6 (33%) of the 18 subjects classified. Of the remaining subjects the independent hierarchical model was superior for 7 subjects and the multiplicative hierarchical model was superior for 5 subjects. For both simultaneous and shifted patterns, neither musical training nor perceptual streaming greatly affected the integrated organization adopted by subjects.

Timing measures

The previous analyses have shown that some form of integrated organization was used by the majority of subjects in this experiment, regardless of pattern, musical training, or perceptual streaming. The present results, therefore, confirm those obtained by Jagacinski et al. (1988), and suggest the rejection of the perceptual-dominance hypothesis. Jagacinski et al. (1988), however, did find some support for a perceptual-motor-facilitation hypothesis. Subjects who synchronized their taps to integratable tone sequences produced more correct response cycles and lower error variability than subjects who synchronized to streamed tone sequences. That is, performance was better when tone pre-

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[1] As the least-squares model parameters correspond to timekeeper variances and a common motor-delay variance, the values should all be positive. Negative parameter estimates are uninterpretable (Jagacinski et al., 1988).

Table 3. Timing measures for Day-2 training trials

	Integrated tones		Streamed tones	
	Mus	Nonmus	Mus	Nonmus
Percentage of correct cycles				
Simultaneous	99	96	97	84
Shifted	99	99	83	81
Absolute deviation (ms)				
Simultaneous	15	19	20	62
Shifted	39	46	62	130
Ratio (I_2/I_4)				
Simultaneous (.50)	.48	.49	.49	.48
Shifted (.27)	.39	.31	.50	.41
Cycle initiation (ms)				
Simultaneous (0)	3	4	1	3
Shifted (100)	97 (23–186)	128 (120–139)	102 (20–178)	236 (103–400)
Number of subjects	2	5	1	1

Note: Mus = musicians; Nonmus = nonmusicians

sentation (integrated tones) matched the motor organization (integrated) adopted by subjects.

To determine whether a similar perceptual-motor-compatibility effect was evident in our data, the percentage of correct-response cycles and absolute-timing error were examined for the last 15 trials in the continuation task on Day 2 (Table 3). Three-way analyses of variance (ANOVA's) with factors of Musical Training (musicians, non-musicians), Pattern (simultaneous, shifted), and Tone (integrated, streamed) were conducted on the performance measures.

Correct-response cycles. The greatest possible number of correct-response cycles was 450 – i. e., 15 trials × (32–2) cycles per trial. The ANOVA performed on the percentage of correct cycles revealed only a significant effect of tone, $F(1,40) = 11.73, p < .01$. As was predicted by the perceptual-motor facilitation hypothesis, integrated tones produced a significantly higher percentage of correct cycles (98.86) than did streamed tones (86.27).

Absolute deviation. As a global measure of how accurately the polyrhythm was reproduced, a deviation score was obtained by the summing of the absolute time differences between the corresponding intervals in the response and target sequences. The mean of these deviation scores was then computed across the correct cycles in a trial as a measure of absolute timing error (see Table 3). The three-way ANOVA yielded a main effect of pattern, $F(1,40) = 17.54, p < .01$. The reproduction of the simultaneous pattern was more accurate (28.93 ms) than the reproduction of the shifted pattern (69.07 ms). The effects of musical training, $F(1,40) = 9.91, p < .01$; tone, $F(1,40) = 16.34, p < .01$, and their interaction, $F(1,40) = 6.63, p < .05$, were also significant. A simple main-effects analysis of the Musical Training × Tone interaction showed that non-musician performance, as predicted by the perceptual-motor-facilitation hypothesis, was significantly less accurate in the streamed-tone condition (95.83 ms) than in the integrated-tone condition (32.37 ms). However, the mean deviation scores of musically trained subjects, although in the predicted direction, did not differ significantly in the streamed and in the integrated conditions (40.92 ms and 26.86 ms, respectively). In addition, musically trained subjects performed significantly more accurately than non-musicians when the tones were streamed, but not when the tones gave an integrated percept.

These results provide further support for the perceptual-motor facilitation hypothesis. More accurate tapping performance was obtained with integrated tones than with streamed tones. In terms of absolute timing error, the simultaneous pattern was also reproduced more accurately than was the shifted pattern, by both musically skilled and unskilled subjects. The large timing error produced by the shifted stimulus pattern suggests that considerable distortion of the intertap intervals occurred. To examine the reproduction of the two patterns in more detail, two further measures of performance were analyzed.

Interval ratio. One effect of shifting the right-hand taps 100 ms later in the cycle (i. e., the shifted pattern) is to alter the phase relationship between the two hands in the production of the polyrhythm. In both versions of the 3:2 polyrhythm the right (fast) hand was to tap every 433 ms and the left (slow) hand every 650 ms. However, in the simultaneous pattern the between-hand interval I_2 (see Fig. 1) should be 217 ms in duration, giving a ratio (I_2/I_4) of .50 (217:433), whereas in the shifted pattern, I_2 should be 117 ms, producing a ratio of .27 (117:433).

The I_2/I_4 ratios produced by subjects in the two patterns are shown in Table 3. Two general observations can be made from the ratio data: (a) the .50 ratio in the simultaneous pattern was reproduced with a high degree of accuracy by both groups of subjects, regardless of whether the tones encouraged an integrated or a streamed percept; (b) in the reproductions of the shifted pattern, subjects showed a general tendency toward a ratio of .50 rather than .27. This tendency was particularly evident when the tones were streamed.

These general effects were confirmed by the three-way ANOVA, which revealed significant main effects of pattern, $F(1,40) = 13.53$, $p < .01$; tone, $F(1,40) = 5.45$, $p < .05$; and their interaction, $F = (1,40) = 6.97$, $p < .05$. Analysis of the Pattern × Tone interaction showed that pattern was a significant effect when the tones were integrated, but not when they were streamed. In addition, streaming the tones had an effect on the ratio produced in the shifted pattern, but not in the simultaneous pattern. There was no main effect of musical training, although the Musical Training × Pattern interaction approached significance, $F(1,40) = 3.67$, $p < .06$. The two subject groups did not differ in the simultaneous pattern, but in the reproduction of the shifted pattern the non-musician group actually produced a mean ratio (.36) closer to the target ratio .27 than did the musician group (.46).

Cycle initiation. In the simultaneous pattern, the two hands tapped simultaneously at the beginning of each cycle, whereas in the shifted pattern the left hand tapped first, followed 100 ms later by the right hand (see Figure 2). As is shown in Table 3, subjects were able to produce ITIs accurately with mean values close to 0 ms in the simultaneous pattern. Large inter-subject differences, however, were evident in producing the 100-ms delay between L1 and R1 in the shifted pattern. The range of values for each group of 6 subjects performing the shifted pattern are shown in brackets. Five of the 12 musically trained subjects produced initial ITIs of less than 70 ms (range 20–69 ms). In contrast, non-musician subjects tended to exaggerate the difference between the two taps.

It appears, therefore, that few subjects in the present experiment were able to reproduce the shifted pattern accurately. In fact only 9 of the 24 subjects tested on the shifted pattern could be said to have produced both a satisfactory initial delay (range 100–186 ms) and a between-hand I_2/I_4 ratio (range .265–.310). The distribution of these subjects across groups is shown at the bottom of Table 3.

Discussion

Previous studies have suggested that perceptual factors, i.e., auditory-pattern structure, or motor factors, i.e., cycle initiation, might account for the lack of a parallel motor organization in polyrhythmic tapping. In the study reported in this paper, we were interested in whether a parallel organization would be induced when both perceptual and motor factors encouraged independent control of the two movement streams. Although the streaming of the tones and/or the shifting of the motor pattern for one hand in relation to the other did affect performance accuracy, these factors had no obvious effect on the motor organization adopted. That is, nearly all the subjects in this study appeared to use, with varying degrees of success, an integrated strategy that involved the interleaving of the movements of the two hands. This was true for skilled and unskilled subjects, for training and transfer trials, and for both versions of the 3:2 polyrhythm. As such, these findings replicate those obtained by Jagacinski et al. (1988), in which they used a synchronization task and extended them to a continuation paradigm.

The identification of the particular integrated model used by subjects through regression analysis revealed that, for the simultaneous pattern, a chaining structure was the most frequently used way of interleaving the timing of the two hands. In contrast, Jagacinski et al. (1988) found that the multiplicative hierarchical model was superior for 6 of 8 subjects. One possible explanation for this discrepancy between the two studies is that Jagacinski et al.'s subjects received some practice trials in which the cycle duration was varied sinusoidally. As these authors suggested, these practice trials may have encouraged the adoption of the multiplicative hierarchical form of organization. An interesting finding in the present study was that, for the shifted pattern, a hierarchical structure was the most commonly used organization. Of the two hierarchical models, the independent hierarchical model was more widely used than the multiplicative hierarchical model. An independent hierarchical structure, in which the fast-hand beats are used as the time base for integrating the timing of the two hands, has been suggested in studies examining performance of more complex polyrhythms (e.g., 4:3, 5:3) (Summers, Ford, & Todd, in press; Summers et al., in press).

The failure of the perceptually streamed stimuli to induce a parallel motor organization in this and Jagacinski et al.'s (1988) study strongly suggests that the perceptual organization does not determine the motor organization. Perceptual streaming, however, did have a significant influence on performance accuracy. The reproduction of both versions of the 3:2 pattern was poorer with streamed tones than with integrated tones, although the effect was larger for the shifted pattern and for non-musicians. This finding supports the perceptual-motor facilitation hypothesis in that performance was enhanced when the perceptual organization (i.e., the integrated percept) was compatible with the dominant motor organization (i.e., the integrated one).

The introduction of a delay between the left- and right-hand taps at the start of each cycle (shifted pattern) also failed to induce a parallel organization. In fact most subjects were unable to perform the shifted pattern accurately, especially with the streamed tones. Musically trained subjects seemed to experience greater difficulty in the training trials with the shifted pattern than did non-musicians. Only three musicians were able to meet the initiation delay and the between-hand ratio criteria (see Table 3), compared to six of the non-musicians.

A number of the musically trained subjects appeared to distort the non-metric shifted pattern to a metric one by decreasing the interval between the left- and right-hand taps at the beginning of each cycle. That is, these subjects distorted the shifted pattern towards the simultaneous pattern. In a study of single-hand tapping, Povel (1981) also noted that musicians were more likely to distort non-rhythmic time patterns to rhythmic ones than were non-musicians. The non-musicians in the present study actually showed a tendency to increase, rather than to decrease, the interval between the initial left- and right-hand taps. This was compensated somewhat by decreasing the length of the R1–R2 interval, but the R2–L2 between-hand interval was lengthened so that the left- (slow-) hand response (L2) fell close to the middle of the R2–R3 interval. Thus, these subjects also attempted to simplify the shifted pattern so that the R2–L2–R3 triplet involved a simple alternation between the hands. Previous studies of polyrhythmic tapping have reported a similar tendency toward between-hand ratios of .5 in the reproduction of complex rhythms (e.g., 4:3, 5:3, 5:4) by unskilled subjects (Summers, Ford, & Todd, in press; Summers et al., in press).

In sum, no evidence was obtained in the present experiment for the use of a parallel motor organization in the performance of a 3:2 polyrhythm. Rather, in this and other studies of polyrhythmic tapping, subjects attempted to interleave the timing of the two hands. Although it is tempting to conclude from these studies that the operation of independent timing mechanisms for the two hands is not possible in concurrent bimanual tasks, the extent to which polyrhythmic-tapping tasks mimic the complex rhythmic performances studied by Shaffer (1981) is open to question. It is worth noting, however, that although Shaffer's pianists did appear to exhibit independent control over the hands, this independence is constrained within the framework of producing a recognizable single piece of music. Thus integration can occur at several levels in complex rhythmic performance. For the highly skilled performer, the ability to decouple the hands at the motor level allows for the expressive features of performance.

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Appendix

The integrated independent hierarchical model

$I_1 = A + m3 - m2$
$I_2 = B + m4 - m3$
$I_3 = D - B + m5 - m4$
$I_4 = D + m5 - m3$
$I_5 = A + B + m4 - m2$

$$
\begin{array}{llll}
\mathrm{Var}(I_1) = & \mathrm{Var}\,A & & + 2\,\mathrm{Var}\,M \\
\mathrm{Var}(I_2) = & & \mathrm{Var}\,B & + 2\,\mathrm{Var}\,M \\
\mathrm{Var}(I_3) = & & -\mathrm{Var}\,B + \mathrm{Var}\,D & + 2\,\mathrm{Var}\,M \\
\mathrm{Var}(I_4) = & & + \mathrm{Var}\,D & + 2\,\mathrm{Var}\,M \\
\mathrm{Var}(I_5) = & \mathrm{Var}\,A + \mathrm{Var}\,B & & + 2\,\mathrm{Var}\,M \\
\mathrm{Cov}(I_1, I_2) = & & & -\mathrm{Var}\,M \\
\mathrm{Cov}(I_1, I_3) = 0 & & & \\
\mathrm{Cov}(I_1, I_4) = & & & -\mathrm{Var}\,M \\
\mathrm{Cov}(I_1, I_5) = & \mathrm{Var}\,A & & + \mathrm{Var}\,M \\
\mathrm{Cov}(I_2, I_3) = & & -\mathrm{Var}\,B & -\mathrm{Var}\,M \\
\mathrm{Cov}(I_2, I_4) = & & & + \mathrm{Var}\,M \\
\mathrm{Cov}(I_2, I_5) = & & \mathrm{Var}\,B & + \mathrm{Var}\,M \\
\mathrm{Cov}(I_3, I_4) = & & \mathrm{Var}\,D & + \mathrm{Var}\,M \\
\mathrm{Cov}(I_3, I_5) = & & -\mathrm{Var}\,B & -\mathrm{Var}\,M \\
\mathrm{Cov}(I_4, I_5) = 0 & & &
\end{array}
$$