Effects of Tempo on the Timing of Simple Musical Rhythms

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Abstract

We investigated whether and how the timing of musical rhythms changes with tempo. Twelve skilled pianists played a monophonic 8-bar melody in 21 different rhythmic versions at 4 different tempi. Within bars, the rhythms represented two isochronous patterns and all possible ordered pairs and triplets of different note values with ratios from the set {3, 2, 1}. The 3-note rhythms also occurred in each of two meters (3/4 and 6/8). Significant deviations from the notated interval ratios were observed in performances of most rhythms, even at the slowest tempo. The observed ratios of the 2-note rhythms changed little with tempo. By contrast, those of the 3-note rhythms showed increasing assimilation of the two longer intervals as tempo increased, while the relative duration of the short interval was barely affected by tempo. These results replicate previous findings of Fraisse (1956), obtained in a nonmetrical and nonmusical context. At fast tempi, the distinction between three different interval durations seems difficult to maintain.

INTRODUCTION

Production and perception of temporal patterns

It is generally recognized that rhythms embodying simple interval ratios are easier to produce and reproduce than more complex temporal patterns. The simplest pattern is an isochronous sequence, in which the interval ratio is 1:1. The next-simplest ratio is 2:1 (or 1:2). Fraisse (1946, 1956) found that rhythmic finger tapping patterns, generated freely without any specific instructions or auditory model, typically had only two interval durations (“long” and “short”) whose ratio was in the vicinity of 2:1. He also observed that auditorily presented patterns with interval ratios smaller than 2:1 tended to be reproduced as 2:1. Following up on these early findings, Povel (1981) investigated the reproduction of cyclically repeated auditory two-interval patterns instantiating various ratios ranging from 1:4 to 4:5. Although the reproduced ratios were related to the stimulus ratios, they were strongly distorted in the direction of 1:2, with 1:2 itself being reproduced most accurately. The distortion was as large for simple ratios (such as 1:3 and 1:4) as for more complex ratios (such as 3:4 and 4:5), and this was true regardless of the musical training of the participants. (For related results, see Essens, 1986; Essens & Povel, 1985; Summers, Hawkins, & Mayers, 1986; Summers, Bell, & Burns, 1989.) However, expert musicians tend to be quite accurate in the production of simple ratios unless they are very large (Collier & Wright, 1995; Sternberg, Knoll, and Zukofsky,1982; Sternberg & Knoll, 1984).

Povel (1981) also found that, when 1:3 and 1:4 ratios occurred in the context of 1:1:1:3 and 1:1:1:1:4 patterns, where they could be organized into a two-level metrical hierarchy with a simple 1:1 ratio at the higher level, they were reproduced much more accurately. (See also Essens & Povel, 1985.) In a much-cited study, Povel and Essens (1985) demonstrated that the accuracy of rhythm reproduction increases with the degree to which a cyclically repeated pattern induces an “internal clock” or regular beat. (See also Drake & Gérard, 1989; Essens, 1986; Summers et al., 1986.) However, Summers et al. (1986) did not find a significant effect of metricality when participants produced patterns that, instead of being presented auditorily, were specified as numerical ratios.

Fraisse (1942-43, 1956) investigated the reproduction of brief temporal patterns (“rhythmic forms”) that were presented auditorily just once, thereby largely avoiding effects of metricality. The results revealed systematic deviations from the interval ratios specified by the auditory model, regardless of whether the ratios were simple or complex. Patterns containing only two intervals of different duration generally showed increased ratios (*contrast*) in reproduction, whereas patterns composed of three different intervals showed reduced ratios (*assimilation*) between the two longer intervals. Similar findings were reported by Summers et al. (1986), who repeated rhythmic patterns cyclically, and by Ihle (1992) in a perceptual task that required listeners to adjust numerically specified interval ratios until they sounded correct. Fraisse (1956) attributed these biases in timing to a basic distinction between *short* and *long* intervals, with contrast occurring between these two categories and assimilation within. He placed the boundary between the two categories at about 400 ms.

Results of many psychophysical and motor control experiments suggest qualitative differences in the perception and production of short and long intervals, though the boundary is usually found to be somewhere between 200 and 300 ms, depending on the paradigm. In temporal interval discrimination, Weber’s law seems to hold approximately in the range from 250 to 1000 ms, but not below 250 ms, where the absolute rather than the relative difference limen tends to be constant (Friberg & Sundberg, 1995; Hibi, 1983). Correspondingly, in the production of isochronous sequences, relative variability (the coefficient of variation) tends to be constant for long intervals (up to 1000 ms or so), but for short intervals absolute variability tends to be constant instead (Hibi, 1983; Peters, 1989; Wing & Kristofferson, 1973). Hibi and Peters independently attributed this difference to automatic grouping of events separated by short intervals. The same argument was already made by Fraisse (1956), who pointed out that only long intervals give rise to a true perception of duration: Whereas short intervals merely separate group elements, long intervals separate individual events or groups of events. The boundary between short and long intervals may reflect a rate limit of a mental clock or oscillator that generates metrical subdivisions and paces discrete motor actions. Evidence for just such a limit at about 250 ms was found in a synchronized tapping study by Semjen, Schulze, and Vorberg (1992). Nagasaki (1987a, 1987b) has found evidence for obligatory grouping of 2, 3, or 4 taps in the timing and force patterns of finger taps at increasing rates.

Short intervals also show the “time shrinking” phenomenon—a subjective shortening of the second of two short successive intervals in a short-long sequence (e.g., Nakajima et al., 1992; ten Hoopen et al., 1995)—whereas long intervals do not. All intervals, however, seem subjectively longer than their physical durations by about 80 ms (Nakajima, 1987). Thus, interval ratios are generally perceptually distorted, especially within the range of short durations.

This implies that simple interval ratios must be distorted in (re)production to be perceived as simple ratios, especially at fast tempi. However, this is not the only factor that affects rhythm production.

Performance of musical rhythms

The research reviewed so far was conducted outside a musical context, and the tasks did not require special musical skills. Music performance introduces additional complexity. Gabrielsson's classic work on rhythm performance from musical notation (Gabrielsson, 1974; Gabrielsson, Bengtsson, & Gabrielsson, 1983) revealed many systematic deviations from mechanical exactitude, but they were often of a context-dependent or performer-specific nature. For example, ratios of 2:1 and 3:1 were typically reduced, but sometimes enhanced. Some of the deviations were evidently due to musical phrase structure or expressive characterization, due to the variety of materials used. Tempo, which was not controlled or systematically varied, also may have played a role. One rather general tendency was to deviate from a 1:1 ratio between two successive short notes that were followed by a longer note by playing the second short note longer than the first. This was also observed by Drake and Palmer (1993) in pianists' productions of simple rhythms, and by Repp (1999) in performances of Chopin preludes; it persisted even when the pianists were instructed to play mechanically or in synchrony with a metronome. Since the longer note following the two short notes defined the end of a rhythmic group, the phenomenon may be interpreted as group-final lengthening. A corresponding subjective shortening of short group-final intervals occurs in perception (Drake, 1993;

Drake, Botte, & Gérard, 1989; Penel, 2000). This shortening is reminiscent of the time-shrinking phenomenon, referred to above.

Several researchers have investigated the effect of deliberately varied metrical structure, specified by musical notation, on performance timing in simple materials. Sloboda (1983, 1985) found that metrical structure was communicated by pianists to listeners, but that it was encoded primarily in dynamics and articulation, not in timing. Drake and Palmer (1993) likewise found few reliable effects of meter on timing. This was also true in a recent study of rhythmic finger tapping, in which auditory rhythms varying in implicit or explicit metrical structure had to be reproduced (Repp & Saltzman, submitted). Clarke (1985) found some reliable effects on timing, but they represented a complex interaction between meter and other structural factors. Metrical structure is an abstract property that is not necessarily conveyed in performance parameters, though it can be.

Other studies of musical timing have focused on the ubiquitous deviations from temporal regularity that occur in the expressive performance of musical compositions (e.g., Palmer, 1989, 1996; Repp, 1992a, 1998a; Shaffer, 1981; Todd, 1985). Expressive timing variations have been found to be related mainly to the grouping and phrase structure of the music, with group-initial and group-final lengthening being common, though other aspects of musical structure may also affect timing. Corresponding distortions have been found in the perception of timing in rich musical contexts (e.g., Repp, 1992a, 1998a). These studies have usually been concerned with systematic variation in the relative durations of successive intervals that are notationally equal. Expressive timing constitutes a quasi-continuous modulation of the tempo, which is best observed when events occur at a steady rate. By contrast, rhythms exhibit temporal diversity and often repetition of temporal patterns. Rhythm production generally requires a steady, unmodulated tempo. Strong rhythmicity and expressive timing are largely incompatible; their origins may be seen to lie in dance and song, respectively.

To explain timing control in piano performance, Shaffer (1982, 1985; Shaffer, Clarke, & Todd, 1984) postulated two timekeeping mechanisms, one that paces the basic metrical pulse in a flexible way (expressive timing) and another that controls the execution of groups of rapid notes via “motor procedures” relative to the metrical pulse. These rhythmic groups are characterized by short temporal intervals, and if they are cyclically repeated, they reduce the flexibility of the metrical pulse. Rhythmic timing concerns the timing of the motor procedures in this framework.

The influence of tempo on rhythmic timing

A much-discussed issue in research on motor control is whether the temporal structure of an action remains relationally invariant (i.e., proportional to total duration) when the tempo changes. In an influential paper, Schmidt (1985) postulated the existence of generalized motor programs that have a multiplicative rate parameter. Other authors have debated and modified this notion (see, e.g., Gentner, 1987; Heuer, 1981; Vorberg & Wing, 1996). Heuer (1988) has pointed out that relative invariance at a central level need not be reflected in observable proportionality because of motor execution delays (Wing & Kristofferson, 1973); however, a linear relationship should hold between observed interval durations and total duration. Vorberg and Wing (1996) have further elaborated this idea. Heuer, Schmidt, and Ghodsian (1995) argued that relationally invariant timing is most likely to hold for “rapid, discrete actions performed in closed, stable environments” (p. 344). We were interested in whether this may apply to musical rhythms.

Repp (1994, 1995) examined whether expressive timing patterns in two pianists’ performances of a Schumann piece at three tempi were relationally invariant. He found only small deviations from proportionality, probably because the music was slow and not strongly rhythmic. By contrast, Desain and Honing (1994) found considerable deviations from proportional scaling in a pianist’s performances of a Beethoven excerpt at three tempi. This was probably due to the generally faster event rate and greater rhythmic complexity of the music. In particular, the piece contained a number of very short intervals (grace notes), whose timing definitely did not scale proportionally, probably because their acceptable duration had a lower limit (see also Windsor et al., 1999). These results suggest that, while relative invariance may hold approximately for expressive timing (where only long intervals are involved), it may not hold for rhythmic timing (patterns of long and short intervals).

Fraisse (1956) already explored the effect of tempo on rhythmic timing, albeit in the reproduction of nonmusical and nonrepetitive “rhythmic forms”, and found that both within-category assimilation and between-category contrast among temporal intervals became larger as the tempo increased. However, when the tempo was increased to a point beyond which short intervals could not be shortened further (for kinematic reasons in tapping with a single finger), then only longer intervals were shortened, which led to a reduction of contrast between short and long intervals. Therefore, contrast tended to be maximal at a moderate tempo, though this may have been an artifact of the tapping task.

A lower limit for short intervals also played a role in studies by Collier and Collier (1996) and Friberg and Sundström (1997) on the effect of tempo on the “swing ratio” of jazz drummers. The swing ratio is the ratio of the two shorter intervals in a cyclically repeated 3:2:1 (two-beat, 6/8) rhythmic pattern. This 2:1 ratio was found to exhibit contrast at slow tempi but assimilation at fast tempi, and it was closest to 2:1 when beat durations were between 300 and 400 ms. Friberg and Sundström noted that the shorter interval reached a lower limit of about 100 ms at fast tempi. Whether this limit represented a motor limitation is unclear because a perceptual adjustment task yielded similar results.

Collier and Wright (1995) trained percussionists to produce various two-interval ratios, cyclically repeated. Their main finding was that training on arbitrarily complex ratios did not transfer from a faster to a slower tempo, which argues against a single motor program with an adjustable rate parameter. However, they also found tendencies towards reduction of simple ratios (assimilation) at the faster tempo but towards contrast at the slower tempo. To explain these results, they hypothesized a tempo-dependent asymmetry in processing delays in the execution of intervals of different duration. This interpretation enabled them to maintain the assumption that rhythm production is driven by a central timekeeper that generates precise simple ratios (cf. Heuer, 1988; see also Ihle, 1992).

When the tempo of a rhythm is changed, perceptual reorganization (regrouping) may occur, which makes it difficult to recognize the same rhythm at different tempi (Handel, 1993). Similarly, in music performance, the events in notationally identical rhythms may be grouped in different ways and timed differently at different tempi (Clarke, 1982). As long intervals turn into short intervals, larger groups of events are formed.

Some studies have examined the effects of tempo on rhythmic timing from a dynamic systems perspective. This research has generally focused on polyrhythms (really, polymetric sequences) executed by the two hands. For example, Peper, Beek, and van Wieringen (1995a, 1995b) have shown that polyrhythms embodying complex ratios, performed by expert drummers, tend to revert to simpler ratios as the tempo is increased. Thus, for example, a 5:8 ratio (here the ratio is between constant within-hand intervals) changed to 1:1 or 1:2, occasionally to 2:3. The simple ratios were considered the strongest attractors in a dynamic regime, and the hands were regarded as coupled nonlinear oscillators whose coupling strength decreases as the movement rate increases, which leads to instability of weaker attractors. However, coupling of limbs may not be the crucial factor, as results similar to those in bimanual coordination have been obtained in unimanual production of rhythms (Semjen & Ivry, 2001). In fact, motor coordination may be governed largely by perceptual constraints (Mechsner, Kerzel, Knoblich, & Prinz, 2001; Semjen & Ivry, 2001). Thus, assimilation and contrast effects in rhythm production could be interpreted as drifts towards simple ratios that represent attractor states of a nonlinear dynamical perceptual system consisting of coupled oscillators (Large, 2000).

Purpose of this study

We investigated the effect of tempo on rhythmic timing in a simple musical context, using a systematically constructed set of materials whose different temporal intervals represent all possible ordered ratios of the integers

1, 2, and 3. Thus we constructed 7 melodies with 2 notes per bar whose temporal ratios were the 6 pairwise combinations of the three integers or 1:1, and also 7 melodies with 3 notes per bar whose temporal ratios were the 6 possible orderings of the three integers or 1:1:1. The 3-note melodies, moreover, were performed in two meters, either 3/4 (i.e., triple subdivision of the bar) or 6/8 (i.e., duple subdivision). These materials were performed by skilled pianists from musical notation at four different tempi. Because successive notes were played with different fingers, a lower limit to the production of short intervals was not expected to play a role.

We expected to find, in accord with earlier research (e.g., Gabrielsson, 1974; Gabrielsson et al., 1983), that musical rhythms are generally not played with exact integer interval ratios, and we wondered whether the pattern of deviations would be in accord with findings obtained by Fraisse (1956) and others in nonmusical contexts. We also wondered whether the timing deviations in the three-interval rhythms would depend on the notated metrical structure (3/4 or 6/8). Our main purpose, however, was to determine whether the observed timing deviations would be relatively invariant across different tempi. On the basis of earlier results (e.g., Collier & Wright, 1995; Desain & Honing, 1994; Fraisse, 1956; Friberg & Sundström, 1997), we expected to find departures from relative invariance. In accordance with predictions of dynamic systems theory (Peper et al., 1995a, 1995b; Treffner & Turvey, 1993), these deviations were expected to be in the direction of simpler interval ratios, especially in 2-note rhythms. For 3-note rhythms, Fraisse’s (1956) observations on changes of assimilation and contrast with tempo provided a basis for predictions and comparisons.

METHODS

Participants

The participants were 12 skilled pianists (semi-professional to professional level) who were paid for their participation. Six of them were students at Yale University (five undergraduates and one graduate student) who were taking regular lessons with a junior faculty pianist in the School of Music and were studying advanced repertoire. The other six were “first study” pianists (five undergraduates and one postgraduate) at the University of Leeds who were taking performance courses for credit.

Materials

The musical materials consisted of rhythmic patterns carried by simple monophonic melodies. The melodies, time signatures (meters), rhythms, and interval ratios are shown in Table 1. The two melodies, shown in their evenly timed versions, served as carriers for the various rhythms. The 3-note (per bar) melody is a simple elaboration of the 2-note (per bar) melody. Each melody consists of two 4-bar half-phrases, and each half-phrase ends with a long note that occupies its final bar. The prescribed fingering is indicated by the small numbers above the note heads. Below each melody, the various rhythmic patterns are shown in a nonmusical notation (explained below). These patterns were applied to bars 1–3 and 5–7 of each melody. Thus, each rhythm was repeated 6 times within a melody. (Only rhythmically homogeneous melodies were used.) The rhythms applied to the 2-note melody required 3 different time signatures (2/4, 3/8, and 5/8). The 3-note rhythms required only a single time signature (either 3/4 or 6/8), but each rhythm occurred with each of these two time signatures.

Insert Table 1 here

The rhythms are represented in Table 1 by a simple symbolic notation that includes metrical subdivisions in the form of parentheses. (In terms of musical note values, “x” is an eighth note, “x–“ a quarter note, and “x—“ a dotted quarter note; as the playing style was *legato,* there were no true rests in any of the rhythms.) Of the 2-note rhythms, only those in 2/4 meter can be subdivided in a binary fashion into two beats, each encompassing two eighth-note sub-beats (2 x 2). For the 2-note rhythms in 3/8 and 5/8 meters, no such metrical hierarchy can be constructed; here the elementary metrical level corresponding to the shortest temporal units (eighth notes) is immediately subordinate to the bar. The 3-note rhythms in 3/4 meter have ternary subdivisions (3 x 2 eighth notes per bar), while those in 6/8 meter have binary subdivisions (2 x 3 eighth notes per bar). The interval ratios of the isochronous versions are referred to as 2:2 and 2:2:2 (rather than 1:1 and 1:1:1) to indicate that the note values involved are quarter notes.

The tempi employed are listed in Table 2. They are specified in metronome ticks per minute. Importantly, the ticks of the metronome always corresponded to bars (i.e., downbeats), not beats. Thus they did not indicate any metrical subdivision of the bar, which was up to the participants’ cognitive strategies. The metronome rate varied with the time signature, so as to keep the nominal interval durations constant across time signatures. The quarter-note and eighth-note durations implied by the metronome settings are listed in the last two columns of Table 2. The durations of eighth notes (the shortest units) were generally within the range of obligatory grouping, except possibly at the slow tempo, and quarter notes entered that range at the fast tempo. This fact was expected to cause particular difficulty with syncopated rhythms (discussed further below), which then would have to be planned and executed in terms of units larger than the beat. Note that rhythms in 6/8 meter had a possible advantage here over rhythms in 3/4 meter because their metrical subdivision (corresponding to a dotted quarter note) was 50% longer and thus did not enter the obligatory grouping region even at the very fast tempo. Thus, whereas the lowest level of the metrical hierarchy might be obliterated in 3/4 meter when the tempo gets fast, the metrical hierarchy might be preserved in 6/8 meter.

Insert Table 2 here

Procedure

The 21 rhythmic melodies were presented in musical notation on separate sheets. In the case of the 3/4 and 6/8 time signatures, the musical notation reflected the metrical structure in the way ties were used. (For example, the first interval in the 3:1:2 rhythm was notated as a quarter note tied to an eighth note in 3/4 meter but as a dotted quarter note in 6/8 meter.) The music sheets remained in the same order for each of the four tempi, which proceeded from slow to very fast. That is, all materials were played at one tempo before they were played at a faster tempo. The order of the different meters was fixed as well (2/4, 3/8, 5/8, 3/4, and 6/8), but the order of the rhythms within each meter was varied between participants in a counterbalanced fashion, with the exception that the evenly timed rhythms (2:2 or 2:2:2) always occurred first in their respective time signature groups.

The Yale pianists played on a Yamaha Clavinova CLP-611 digital piano and used the built-in metronome. The Leeds pianists played on a Yamaha Clavinova CLP-250 and used an external Seiko Quartz digital metronome. The pianists monitored the sound (“Piano 1”) over headphones, and the experimenter listened over a second pair of earphones. For each group of rhythms with the same time signature, the experimenter set the metronome at the appropriate rate (see Table 2). For each individual rhythm, the pianist first turned on the metronome and imagined the required rhythm in synchrony with the downbeats. When s/he felt ready to play, s/he turned the metronome off and began to play as soon as possible. Each pianist played with the right hand in *legato* style (i.e., without inserting silences between the notes), using the indicated fingering (see Table 1). If a production did not seem satisfactory to the pianist or the experimenter, it was repeated immediately. A maximum of three attempts was permitted, to keep the session duration within limits. Only the final attempts were analyzed. The performances were recorded in MIDI format and saved as text files, which were later imported into a spreadsheet/graphics program for analysis.

RESULTS AND DISCUSSION

Initial inspection of the data revealed that the average results for the Leeds and Yale pianists were strikingly similar. Therefore, the data of the two groups were pooled in all following analyses.

Indicators of relative difficulty

Four factors were expected to cause differences in relative difficulty among the rhythms. One was the number of different interval durations: Evenly timed rhythms were expected to be easier than unevenly timed rhythms, and 2-note rhythms were expected to be easier than 3-note rhythms, on the whole. The second property was syncopation—the absence of an event in a metrically strong position. Syncopation occurred only in 3-note rhythms (see Table 1). Among the uneven rhythms in 3/4 (3 x 2) meter, the ones containing two syncopations (3:2:1, 1:2:3) were expected to be more difficult than the others, which contained only one syncopation. Among the rhythms in 6/8 (2 x 3) meter, those containing one syncopation (2:3:1, 1:3:2, 2:2:2) were expected to be more difficult than the others, which were non-syncopated. Because the 3/4 rhythms were more syncopated than the 6/8 rhythms, they also were expected to be more difficult overall. The third factor was the order of the two intervals within a bar or non-syncopated beat. We expected rhythms to be easier when the longer duration preceded the shorter one, because it is more natural for a longer event to coincide with a metrically strong position. The fourth factor was meter as such: The 5/8 meter is arguably more difficult than the other meters. In addition, the difficulty of most rhythms was expected to increase as tempo increased.

Repeated attempts. The total number of repeated attempts provided a rough index of the relative difficulty of the different rhythms. These data are shown in Table 3. Repeated attempts did not increase steadily as tempo increased, although they were most frequent at the very fast tempo. Increasing practice or lowered criteria during the experimental session may have counteracted the increasing difficulty of the task, or else a moderate tempo was indeed most comfortable. There were considerable differences among rhythms, as expected. Among the 2-note rhythms, those in 5/8 meter were clearly more challenging than the others. Among the 3-note rhythms in 3/4 meter, those with double syncopations (3:2:1, 1:2:3) were repeated most often, those with single syncopations (2:1:3, 1:3:2) less often, and those with dotted rhythms (3:1:2, 2:3:1, which perhaps should not be considered syncopated at all) least often. Among the 3-note rhythms in 6/8 meter, those with syncopations (2:2:2, 2:3:1, 1:3:2) were repeated about as often as those without syncopations having 1:2 ratios within beats (3:1:2, 1:2:3), but those with 2:1 ratios within beats (3:2:1, 2:1:3) were repeated less often. Among two-note rhythms, too, 1:2 was repeated more often than 2:1. These results are generally in agreement with our predictions regarding the relative difficulty of the rhythms.

Insert Table 3 here

Bar durations (tempi). We expected that, in the absence of a running metronome, the faster tempi would be slowed down somewhat, perhaps in proportion to the difficulty of individual rhythms.[1] The relevant data are shown in Table 4. Each number represents the percentage deviation of the average bar duration from the interval specified by the metronome prior to performance. The numbers in parentheses are double standard errors (~95% confidence intervals), and the significance levels of the deviations are indicated by asterisks. It is evident that, with few exceptions, the metronome tempo was followed accurately at the slow tempo. At the medium tempo, however, the pianists generally played slower by up to about 10%, and at the fast and very fast tempi they played slower by up to about 20%, on the average. Thus the intended tempo range was somewhat compressed in execution. The striking differences between 2:2:2 (3/4) and 2:2:2 (6/8), and between 3:2:1 (3/4) and 3:2:1 (6/8), should be noted. They indicate that the pianists did conceptualize the rhythms differently, presumably in accordance with the prescribed meter, and that the tempo reductions were indeed related to the subjective difficulty of the rhythms. The correlations between the total numbers of repeated attempts (Table 3, last column) and the percentage deviations from each of the four prescribed tempi were –0.18 (n.s.), 0.58 ($p < .01$), 0.69, and 0.62, respectively. Thus, the more often a rhythm was repeated, the slower it tended to be played when the tempo was moderate or faster; both measures presumably reflect the relative difficulty of the rhythms.[2]

Insert Table 4 here

Two-note rhythms

The tone inter-onset intervals of individual productions were converted to proportions by dividing each interval by the total bar duration. For graphic presentation, these proportions were then averaged across the 6 bars and across the 12 pianists, and double standard errors (~95% confidence intervals) were calculated across pianists. Figure 1 shows these results for the 2-note rhythms. The expected proportions are indicated by the horizontal bars attached to the ordinate of each graph. The two proportions shown are complementary (they sum to 1). For each rhythm, one proportion was submitted to a repeated-measures ANOVA with tempo (4) as the fixed variable. Comparable proportions for pairs of rhythms differing only in the order of the same intervals were submitted to two-way ANOVAs with order (2) as an additional fixed variable. The proportions were first converted to deviations from the expected proportions, so that the significance of the mean deviation, which is indicative of assimilation or contrast, could be assessed as well. A main effect of order then would indicate different degrees of assimilation or contrast in the two rhythms.

Insert Figure 1 here

It is evident from the top panel in Figure 1 that the simple 2:2 rhythm was produced very accurately, as expected, though there was a tendency to lengthen the second interval as the tempo increased. The mean deviation of 0.7% was significant, $F(1,11) = 9.6$, $p < .02$, but the main effect of tempo fell just short of significance, $F(3,33) = 2.8$, $p < .06$.

The first pair of large panels in Figure 1 shows the results for the 2:1 and 1:2 rhythms. In the combined ANOVA there was a significant main effect of order, $F(1,11) = 16.1$, $p < .003$, due to the fact that the 1:2 rhythm exhibited a significant contrast effect with a mean deviation of 2.2%, $F(1,11) = 20.2$, $p < .001$, whereas the 2:1 rhythm did not, $F(1,11) = 0.4$. In fact, the 2:1 rhythm showed assimilation at the slow tempo, which disappeared as the tempo increased; the main effect of tempo was significant, $F(3,33) = 5.6$, $p < .004$. The 1:2 rhythm did not change significantly with tempo, $F(1,11) = 1.1$.

The 3:1 and 1:3 rhythms, which are shown in the center panels of Figure 1, did not show a significant effect of interval order, $F(1,11) = 1.9$. Each rhythm showed significant assimilation—4.5%, $F(1,11) = 20.6$, $p < .001$, and 3.1%, $F(1,11) = 17.2$, $p < .002$, respectively—which did not change with tempo.

The results for the 3:2 and 2:3 rhythms are shown in the bottom panels of Figure 1. These two rhythms differed very strikingly, $F(1,11) = 15.8$, $p < .003$. The 2:3 rhythm showed a clear average contrast effect of 3.9%, $F(1,11) = 24.6$, $p < .0005$, whereas the 3:2 rhythm exhibited a nonsignificant assimilation tendency, $F(1,11) = 1.1$. This tendency was due to only two individuals who exhibited complete assimilation (i.e., close to a 10% difference between expected and actual interval proportions). Their data account for the relatively large error bars for the 3:2 rhythm. There were no such striking individual differences for the 2:3 rhythm. Neither rhythm changed with tempo.

In summary, the 2-note rhythms exhibited surprising stability with changes of tempo, which is consistent with the relative invariance hypothesis. Assimilation and contrast effects were usually already present at the slow tempo and did not increase as the tempo accelerated. These effects could be regarded as tendencies towards simpler ratios: 3:1 and 1:3 tending towards 2:1 and 1:2, respectively, 3:2 towards 1:1 (in two participants only), and 2:3 towards 1:2. However, the absence of an increase in these tendencies with tempo is not consistent with the ratio simplification hypothesis.

Three-note rhythms

The results for the 3-note rhythms are shown in Figures 2 (3/4 meter) and 3 (6/8 meter). The overall impression from these graphs is that, in all rhythms and in both meters, the shortest of the three intervals (1/6) remained proportionally stable with changes in tempo, whereas the two longer intervals assimilated as tempo increased. This is very much in accord with Fraisse's (1956) observations on three-interval rhythmic forms. Repeated-measures ANOVAs were carried out on the deviations from the expected proportions of the two longer intervals. The same rhythms in different meters were analyzed together, so that the fixed variables were interval (2), meter (2), and tempo (4). In these analyses, assimilation (or contrast) of the two longer intervals would be reflected in a significant main effect of interval, and increasing assimilation (or contrast) with tempo by an Interval x Tempo interaction. Effects concerning the third, short interval (whose deviation score was one minus the sum of the deviation scores of the two longer intervals) would be reflected in effects not involving the interval variable.

Insert Figures 2 and 3

on facing pages

The results for the 2:2:2 rhythm are shown in the small panels on top of Figures 2 and 3. As expected, this simple rhythm was produced very accurately in 3/4 meter, though there was a slight tendency to lengthen the final interval as tempo increased. More surprisingly, the 2:2:2 rhythm was also produced very accurately, though with somewhat greater variability across pianists, in 6/8 meter, where it was considered to be rather difficult. The isochronous nature of the rhythm may have facilitated this task and perhaps made a 6/8 mind set difficult to maintain. The main effect of meter was significant, $F(1,11) = 12.2$, $p < .006$, because in 6/8 meter there was no tendency to lengthen the final interval; on the contrary, this interval tended to be shortened somewhat at the slow tempo. Nevertheless, the final interval proportion tended to increase as tempo decreased in both meters, which was reflected in a significant main effect of tempo, $F(3,33) = 3.4$, $p < .03$.

The 3:2:1 rhythm was expected to be significantly more difficult in 3/4 meter, where it was doubly syncopated, than in 6/8 meter, where it was not syncopated and quite natural because the interval durations were congruent with the metrical hierarchy. This expectation is borne out by a larger assimilation effect and greater variability (larger error bars) in the 3/4 condition. There was a significant grand mean deviation, $F(1,11) = 10.2$, $p < .009$, due to a slight lengthening of the final short interval, regardless of meter or tempo. The two longer intervals converged as the tempo increased, but more so in 3/4 than in 6/8 meter. This finding was reflected in a main effect of interval, $F(1,11) = 41.6$, $p < .0001$, an Interval x Tempo interaction, $F(3,33) = 4.4$, $p < .02$, and an Interval x Tempo x Meter interaction, $F(3,33) = 3.5$, $p < .03$.

The 3:1:2 rhythm was expected to be easy in 3/4 meter but more difficult in 6/8 meter, where the shortest note received a metrical accent. This prediction is borne out by greater variability at the slower tempi and by greater assimilation of the two long intervals in the 6/8 condition. In fact, the assimilation effect in 6/8 meter was surprisingly strong and virtually complete at the very fast tempo, resulting in a rhythm whose intervals were related 2.5:1:2.5 (5:2:5). The short interval was produced very accurately. The assimilation effect (the main effect of interval) was highly significant, $F(1,11) = 95.0$, $p < .0001$, as were the Interval x Meter interaction, $F(1,11) = 26.3$, $p < .0001$, and the Interval x Tempo interaction, $F(3,33) = 9.8$, $p < .0002$.

The 2:3:1 rhythm was expected to be more difficult in 6/8 meter, where it is strongly syncopated, than in 3/4 meter, where it is only weakly syncopated. This prediction is borne out only by the greater variability in the 6/8 condition. Of all 3-note rhythms, the 2:3:1 rhythm was least subject to assimilation or change with tempo. Nevertheless, there were some significant effects. The shortest interval tended to be lengthened, which led to a significant grand mean deviation, $F(1,11) = 11.0$, $p < .007$. This lengthening was more pronounced in 6/8 than in 3/4 meter, as indicated by a significant main effect of meter, $F(1,11) = 5.8$, $p < .04$. The main effect of interval, $F(1,11) = 8.3$, $p < .02$, reflects some slight assimilation of the two longer intervals, but it did not interact with tempo.

The 2:1:3 rhythm was expected to be easier in 6/8 than in 3/4 meter, because of the metrically accented short note and syncopation in the latter. Surprisingly, however, it was the 6/8 condition that showed more assimilation and greater variability. The main effect of interval, reflecting assimilation of the two longer intervals, was highly significant, $F(1,11) = 29.9$, $p < .0003$, and interacted with meter, $F(1,11) = 18.3$, $p < .002$, and with tempo, $F(3,33) = 7.9$, $p < .0005$. The short interval was produced very accurately and with low variability. However, there was a progressive relative shortening of the short interval as the tempo increased, and this led to a significant main effect of tempo, $F(3,33) = 7.5$, $p < .0007$.

The 1:3:2 rhythm was expected to be very difficult in 6/8 meter, but less so in 3/4 meter. The stronger assimilation in the 6/8 condition bears this out, although variability was high in both meters. The main effect of interval, the indicator of assimilation or contrast, was highly significant, $F(1,11) = 42.4$, $p < .0001$, and interacted with meter, $F(1,11) = 8.2$, $p < .02$, and with tempo, $F(3,33) = 6.7$, $p < .002$. Although it seems that the short interval was somewhat lengthened, the grand mean deviation fell short of significance. However, there was a main effect of tempo, $F(3,33) = 3.3$, $p < .04$, due to a progressive reduction of the lengthening of the short interval as the tempo increased.

Finally, the 1:2:3 rhythm was predicted to be very difficult in 3/4 meter because of double syncopation, but not easy in 6/8 meter either because of the strongly accented short note. Assimilation of the two longer intervals increased with tempo in both conditions and was virtually complete at the very fast tempo. The main effect of interval was highly significant, $F(1,11) = 82.6$, $p < .0001$, and it interacted with tempo, $F(3,33) = 24.6$, $p < .0001$, and weakly with both tempo and meter, $F(3,33) = 3.5$, $p < .03$. The short interval was again produced rather accurately, though there was a main effect of meter, $F(1,11) = 11.0$, $p < .007$, because the short interval was lengthened somewhat in 3/4 meter.

In summary, assimilation of the two longer intervals occurred and increased with tempo, regardless of whether these intervals were adjacent within the bar or across bar lines. The degree of assimilation was not straightforwardly related to the predicted difficulty of the rhythms; for example, the difficult 2:3:1 rhythm showed the least assimilation. The variability of the data across participants seemed a better indicator of relative difficulty. The short interval was produced very accurately in bar-medial position (3:1:2 and 2:1:3), was lengthened slightly in bar-initial position (1:3:2 and 1:2:3), and was lengthened somewhat more in bar-final position (3:2:1 and 2:3:1).

Phrase-final lengthening

Not unexpectedly, the bar preceding the final long note (bar 7) was lengthened relative to the other bars; this phrase-final lengthening occurred in all 21 rhythms and at all four tempi. There was also a slight tendency to lengthen the bar at the end of the first half-phrase (bar 3). These results are summarized in Figure 4. Two-way repeated-measures ANOVAs with the variables of tempo (4) and bar (6), and with either pianists (12) or rhythms (21) as the random variable, yielded highly reliable ($p < .0001$) main effects of tempo, $F_1(3,33) = 25.0$, $F_2(3,60) = 53.1$, and of bar, $F_1(5,55) = 10.9$, $F_2(5,100) = 36.3$, as well as an interaction, $F_1(15,165) = 3.8$, $F_2(15,300) = 5.9$, due to more pronounced phrase-final lengthening at the faster tempi.

Insert Figure 4 here

The phrase-final lengthening amounted to a local tempo change (i.e., expressive timing), and one question of interest was whether the rhythmic intervals in the lengthened bar were stretched proportionally or whether they were lengthened progressively. The ANOVAs reported in connection with Figures 1–3 actually contained bar (6) as an additional fixed variable. If phrase-final lengthening occurred at the bar level but left the interval proportions within bars unchanged, then there should not have been any significant effects of bar in the ANOVAs on the deviations from the expected interval proportions. However, the main effect of bar was significant for nearly all rhythms, which indicates that the proportions did vary systematically across bars. In the case of the 3-note rhythms, the main effect of bar indicates a change in the short interval relative to the two longer ones. In addition, each 3-note rhythm also showed a significant Bar x Interval interaction, which indicates that the two longer intervals changed in opposite directions. Other interactions with the bar variable were rare and will not be discussed here. It should be noted that there were few interactions of bar with tempo.

Figures 5 and 6 display the deviations from the expected interval proportions as a function of bar, averaged across tempi. The data for the 3-note rhythms (Figure 6) have been averaged across the two meters. The intervals are represented in terms of their order in the bar, with the final interval being highlighted (filled circles, solid lines). It is evident that, in practically all cases, the final interval showed phrase-final lengthening in bar 7. In the 2-note rhythms, this lengthening was necessarily at the cost of the first interval, but in the 3-note rhythms this was also the case, with the second interval showing neither lengthening nor shortening in bar 7. These relationships indicate progressive lengthening within the bar. In 3-interval rhythms there was also a tendency for the final interval to be lengthened in bar 3, at least relative to bar 2, but that lengthening was at the cost of the second interval, not the first. It may be inferred that half-phrase final lengthening was progressive also but had a smaller scope than phrase-final lengthening.

Insert Figures 5 and 6 here

GENERAL DISCUSSION

The aim of the present study was to determine the extent to which changes in tempo affect the performance of relatively simple rhythms on the piano. Although we employed only three basic interval units (note values), the rhythms ranged from extremely easy ones (e.g., 2:2:2 in 3/4 meter) to some that were difficult even at slow performance rates (e.g., 1:2:3 in 3/4). As expected, the patterns which were most syncopated showed larger numbers of repeated attempts and larger deviations from the requested tempo. This is in line with the findings of Povel and Essens (1985), for the degree to which a rhythm is syncopated is closely related to its congruence with a hierarchical metrical grid.

As expected, our findings corroborate earlier results (e.g., Gabrielsson, 1974; Gabrielsson et al., 1983) showing that musical rhythms are rarely performed with the exact interval ratios specified in musical notation. Even at the slowest tempo, significant deviations from the nominal ratios were observed in both 2-note and 3-note rhythms. In the case of 2-note rhythms, most of these deviations can be interpreted as tendencies towards simpler ratios. However, these simple ratios were never actually achieved, so that the produced intervals actually exhibited rather complex ratios. (Note that, for 2:3 and 3:2 rhythms, deviations in either direction can be interpreted as a tendency towards a simpler ratio—assimilation as tending towards 1:1, and contrast as tending towards 1:2

or 2:1, respectively.) Moreover, none of these tendencies increased as the tempo increased, contrary to the ratio simplification hypothesis which originates in research on bimanually executed polymetric rhythms which are considerably more complex in their interval structure than the present 2-note rhythms (e.g., Peper et al., 1995a, 1995b). Our results suggest that a characteristic way of performing each 2-note rhythm is maintained across changes in tempo. The data for 2-note rhythms thus seem more consistent with the relational invariance hypothesis than with the ratio simplification hypothesis; only one of the seven 2-note rhythms (2:1) changed its timing significantly with tempo. It should be kept in mind, however, that manifest non-invariance can reflect central invariance (Heuer, 1988; Vorberg & Wing, 1996), and therefore manifest invariance need not reflect central invariance.

The results were quite different for 3-note rhythms. These results confirm Fraisse’s (1956) observation that addition of a short interval to two longer intervals changes the timing pattern of the longer intervals. Of course, it also changes the meter, but this was not a factor (or only a much weaker factor) in Fraisse’s experiments with “rhythmic forms” that were presented only once. Nevertheless, the present results are basically in agreement with his findings: The short interval was generally timed quite accurately and was little affected by tempo, whereas the two longer intervals showed assimilation which increased as the tempo increased. Importantly, this assimilation occurred regardless of whether the two longer intervals were adjacent or nonadjacent within a bar—in other words, whether or not they were separated by a bar line (since they were always adjacent). If adjacency is a necessary condition for assimilation to occur, then the results suggest that it was the rhythmic group, not the metrical bar, that was subject to temporal deformation.

In another respect, however, our results contradict Fraisse. He (Fraisse, 1956) hypothesized that the assimilation of the two longer intervals in 3-interval rhythms was due to a reduction of contrast between intervals in the “long” category. This interpretation can only be correct if the boundary between short and long intervals is assumed to be flexible, so that even at the very fast tempo (where assimilation was maximal) the shorter of the two longer intervals in our 3-note rhythms still belonged to the “long” category. At that tempo, the nominal interval durations were 100, 200, and 300 ms, so the boundary must have been at less than 200 ms, which is much shorter than what Fraisse seemed to consider the boundary between short and long intervals. It is unclear whether Fraisse truly believed that this boundary was fixed, for he himself had found effects of tempo on interval timing. Even a boundary value as low as 200 ms is still reasonably consistent with psychophysical and motor control findings suggesting that obligatory grouping occurs at temporal separations shorter than about 250 ms (e.g., Hibi, 1983; Peters, 1989) or 200 ms (Handel & Lawson, 1983). Therefore, Fraisse’s short-long distinction could be maintained as long as it is regarded as being highly context-dependent and always contrasting the two longer intervals with the shortest interval in a 3-interval rhythmic group.

Our findings for 3-note rhythms are inconsistent with the relational invariance hypothesis. Although observed interval ratios could show non-invariance because of duration-dependent additive delays (Collier & Wright, 1995; Heuer, 1988), it is difficult to see how this model could explain the relative constancy of the short interval and the increasing assimilation of the two longer intervals as the tempo increased. Small additive delays cannot lead to complete assimilation, as was observed in some rhythms. Also, this model cannot explain why progressive assimilation occurred in 3-note but not in 2-note rhythms.

At the slow tempo, it was possible to subdivide longer intervals by a beat that corresponded to the shortest interval duration (250 ms) or that, in the case of the 3:2 and 2:3 rhythms, was internally generated. (Even so, however, the timing of the rhythms was not exact.) Subdivision became difficult at the moderate tempo and was impossible at the fast tempi because the interval duration was too short for explicit counting or internal beat generation (Semjen et al., 1992). Consequently, the short interval was grouped with the following longer interval, and the beat moved to the next-higher level in the metrical hierarchy. For 2-note rhythms, that level was the bar. As a result, the rhythms within bars had to be produced according to a motor procedure (Shaffer et al., 1985) that apparently was quite successful in maintaining the rhythm. In the case of 3-note rhythms, the subjective beat first shifted to the nominal beat level (3 per bar in 3/4 meter, 2 per bar in 6/8 meter) and then probably to the bar level as the tempo increased further, at least in 3/4 meter. We speculate that the short interval was produced quite accurately because it is mainly responsible for the distinctive quality of the rhythm. The distinction between the two longer intervals seems less important in that regard; it pertains more to low-level metricality, which was corrupted by the fast tempo. Therefore, the metrical regularity of the rhythm within the bar was sacrificed. In effect, the 3-note rhythms became 2-note rhythms in which a short note was attached to one of the longer notes, like a grace note (Windsor et al., 1998). The two longer intervals tended towards a simple ratio (1:1) as they became increasingly difficult to time individually. With some additional assumptions, then, the results for 3-note rhythms seem in accord with the ratio simplification hypothesis.

We also observed phrase-final lengthening in the pianists' performances. This is an effect of expressive timing which is in line with the two-level theory of timing control in musical performance proposed by Shaffer (1982; Shaffer et al., 1985). It seems to reflect a flexible timer that continuously modulates the tempo at the level of functional metrical units. Expressive timing interacted with rhythmic timing: Interval ratios did not remain constant within a lengthened bar but rather exhibited progressive or local (bar-final) lengthening. However, expressive timing was rather limited in our simple materials and contributed little to the overall interval ratios which were computed across 6 bars (see Fig. 5).

In conclusion, our study shows that tempo has a strong effect on rhythmic performance when the rhythm comprises more than two interval durations. Apart from Fraisse's (1956) pioneering studies, data on this issue have been scarce in the psychological literature, particularly with regard to music performance proper. Our findings are relevant to any attempt to model the effect of global tempo on the timing of local events in music performance. Any such model must take into account changes in grouping and metrical structure brought about by tempo changes, which evidently cause changes in local timing patterns, particularly when more than two interval durations are involved.

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FOOTNOTES

[1] It might be asked why we did not ask the pianists to play in synchrony with a metronome, which would have guaranteed precise tempi. We felt that this would have made the task less musically valid. Moreover, the requirement of synchronization would have introduced error correction, which would have affected timing and its variability (see, e.g., Repp, 1999).

[2] Since we analyzed only the last repetition, we do not know whether the tempo decreased in the course of repetitions.

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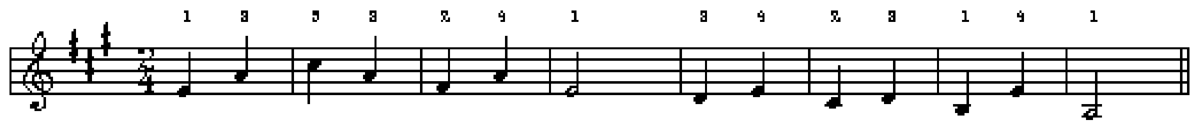
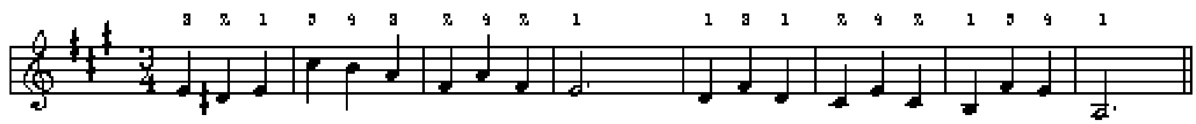
Table 1. The melodies and rhythms (x = note onset; – = sustained note; | = bar line; parentheses = metrical subdivisions).

(1) The two-note melody:



Meter	Rhythm	Ratios
2/4	| (x–)(x–) |	2:2
2/4	| (x–)(–x) |	3:1
2/4	| (xx)(—) |	1:3
3/8	| x–x |	2:1
3/8	| xx– |	1:2
5/8	| x—x– |	3:2
5/8	| x–x— |	2:3

(2) The three-note melody:



Meter	Rhythm	Ratios	Meter	Rhythm	Ratios
3/4	| (x–)(x–)(x–) |	2:2:2	6/8	| (x–x)(–x–) |	2:2:2
3/4	| (x–)(–x)(x–) |	3:1:2	6/8	| (x—)(xx–) |	3:(1:2)
3/4	| (x–)(–x)(–x) |	3:2:1	6/8	| (x—)(x–x) |	3:(2:1)
3/4	| (x–)(x–)(–x) |	2:3:1	6/8	| (x–x)(—x) |	2:3:1
3/4	| (x–)(xx)(—) |	2:1:3	6/8	| (x–x)(x—) |	(2:1):3
3/4	| (xx)(–x)(—) |	1:2:3	6/8	| (xx–)(x—) |	(1:2):3
3/4	| (xx)(—)(x–) |	1:3:2	6/8	| (xx–)(–x–) |	1:3:2

Table 2. The tempi (metronome ticks/s) and equivalent note durations (ms).

	Meter				Note value	
	2/4	3/8	5/8	3/4, 6/8	quarter	eighth
Slow	60	80	48	40	500	250
Moderate	90	120	72	60	333	167
Fast	120	160	96	80	250	125
Very fast	150	200	120	100	200	100

Table 3. Number of repeated attempts (possible maximum per tempo = 24).

Rhythm	slow	medium	fast	very fast	Total
2:2 (2/4)	2	1	1	1	5
3:1 (2/4)	1	1	1	4	7
1:3 (2/4)	0	0	0	3	3
2:1 (3/8)	0	0	1	3	4
1:2 (3/8)	3	3	1	4	11
3:2 (5/8)	7	5	4	1	17
2:3 (5/8)	6	5	6	5	22
2:2:2 (3/4)	4	0	0	3	7
3:1:2 (3/4)	2	2	1	4	9
3:2:1 (3/4)	6	4	7	8	25
2:3:1 (3/4)	2	2	2	1	7
2:1:3 (3/4)	3	0	4	7	14
1:2:3 (3/4)	7	5	5	6	23
1:3:2 (3/4)	2	2	3	6	13
2:2:2 (6/8)	3	4	3	1	11
3:1:2 (6/8)	0	5	1	4	10
3:2:1 (6/8)	1	1	3	2	7
2:3:1 (6/8)	4	3	6	2	15
2:1:3 (6/8)	2	1	0	0	3
1:2:3 (6/8)	4	5	4	3	16
1:3:2 (6/8)	4	2	1	3	10
Total	63	51	54	71	239

Table 4. Percentage deviations of bar durations from metronome interval, with double standard errors in parentheses (* $p < .05$, ** $p < .01$, *** $p < .001$).

Rhythm	slow	medium	fast	very fast
2:2 (2/4)	1.8 (3.9)	-1.6 (2.8)	-2.1 (2.4)	-0.3 (2.4)
3:1 (2/4)	4.1 (4.9)	1.7 (4.0)	3.5 (3.6)	2.9 (3.0)
1:3 (2/4)	3.3 (4.4)	3.1 (2.8)*	6.7 (4.6)**	6.1 (3.8)**
2:1 (3/8)	5.7 (4.8)*	6.4 (3.5)***	10.0 (6.6)**	13.1 (4.1)***
1:2 (3/8)	9.1 (5.0)***	10.6 (3.3)***	14.6 (5.5)***	16.5 (3.6)***
3:2 (5/8)	-1.5 (3.6)	7.3 (4.9)**	16.6 (6.7)***	17.3 (10.9)*
2:3 (5/8)	-0.6 (3.8)	6.5 (5.0)**	14.0 (6.3)***	15.5 (7.4)***
2:2:2 (3/4)	-10.2 (7.1)**	-4.6 (6.9)	-2.2 (4.5)	0.3 (3.7)
3:1:2 (3/4)	-2.5 (4.5)	6.7 (3.1)***	14.8 (5.1)***	14.9 (6.8)***
3:2:1 (3/4)	-2.0 (2.7)	12.5 (4.6)***	20.4 (7.1)***	19.3 (9.8)***
2:3:1 (3/4)	-2.3 (4.1)	6.9 (4.8)**	10.8 (5.6)***	10.3 (5.7)***
2:1:3 (3/4)	-0.6 (1.7)	8.1 (3.4)***	14.2 (5.4)***	14.8 (6.0)***
1:2:3 (3/4)	-1.1 (3.5)	9.0 (5.3)***	17.0 (6.6)***	20.1 (5.0)***
1:3:2 (3/4)	-2.8 (2.6)	9.0 (3.0)***	16.2 (6.5)***	16.7 (3.9)***
2:2:2 (6/8)	-2.7 (4.9)	6.0 (5.0)*	17.7 (8.0)***	17.3 (10.6)**
3:1:2 (6/8)	0.0 (4.7)	10.2 (3.8)***	11.6 (4.2)***	15.4 (6.3)***
3:2:1 (6/8)	-1.9 (4.7)	5.3 (5.3)*	7.3 (4.6)**	1.0 (8.0)
2:3:1 (6/8)	-0.2 (2.7)	7.6 (5.7)**	12.2 (5.8)***	14.5 (7.9)***
2:1:3 (6/8)	-0.8 (4.2)	3.8 (4.0)	7.3 (3.7)***	11.3 (5.7)***
1:2:3 (6/8)	-1.4 (4.4)	10.0 (6.5)**	15.0 (5.3)***	16.7 (7.6)***
1:3:2 (6/8)	-2.2 (2.9)	10.4 (4.8)***	15.1 (5.1)***	23.9 (8.6)***

FIGURE CAPTIONS

Fig. 1. Average proportions of intervals within bars, averaged across bars and participants, with double standard errors, for the 7 2-note rhythms. The heavy bars attached to the ordinates indicate the notated proportions.

Fig. 2. Average proportions of intervals within bars, averaged across bars and participants, with double standard errors, for the 7 3-note rhythms in 3/4 meter. The heavy bars attached to the ordinates indicate the notated proportions.

Fig. 3. Average proportions of intervals within bars, averaged across bars and participants, with double standard errors, for the 7 3-note rhythms in 6/8 meter. The heavy bars attached to the ordinates indicate the notated proportions.

Fig, 4. Average percentage deviations from the bar duration specified by the metronome prior to performance, for the 6 rhythmic bars at the 4 tempi.

Fig. 5. Average percentage deviations from the notated proportions of intervals within each bar, for the 7 2-note rhythms.

Fig. 6. Average percentage deviations from the notated proportions of intervals within each bar, for the 7 3-note rhythms (averaged across the two meters).