Production and Synchronization of Uneven Rhythms at Fast Tempi

Bruno H. Repp
Haskins Laboratories, New Haven, Connecticut

Justin London
Carleton College, Northfield, Minnesota

Peter E. Keller
Max Planck Institute for Human Cognitive and Brain Sciences, Munich, Germany

THIS STUDY EXAMINED PRODUCTION and synchronization of eight uneven rhythms (set A: 2+3, 3+2; set B: 2+2+3, 2+3+2, 3+2+2; set C: 2+3+3, 3+2+3, 3+3+2) at rates that made it difficult to subdivide the component intervals into elementary metrical pulses. The main questions were how interval ratios would change as a function of tempo within this range, and whether metrical downbeat location (which distinguishes the rhythms within each set) would be reflected in any of the dependent measures. Musically trained participants tapped each rhythm cyclically in synchrony with an auditory template and then continued to tap in three ways: self-paced, paced by a sequence of downbeats, or paced by a rapid stream of isochronous subdivisions. Each task was carried out at eight tempi. The third task assessed the temporal limit of subdivision for these rhythms (about 6 Hz), which was exceeded by most tempi. Results showed that the mean long–short (3:2) interval ratio was already larger than 1.5 at the slowest tempo in rhythm sets A and B, and increased with tempo in sets B and C, but did not approach 2. Uneven rhythms thus can be produced without mental subdivision, but only with substantial enhancement of the contrast between long and short intervals. Metrical downbeat location had no reliable effect on interval ratios but was reflected in more forceful downbeat taps and in different alignments of taps with a pacing sequence. In general, effects of temporal grouping (between rhythm sets) outweighed those of metrical interpretation (within rhythm sets).

Received December 2, 2003, accepted January 8, 2005

Uneven Rhythms

MUCH OF THE WORLD'S MUSIC involves uneven rhythms, from African drum patterns to Norwegian Hardanger fiddle tunes. By "uneven" we mean a special relationship between long and short elements in a rhythmic pattern. Consider two cyclically repeated rhythmic patterns, one composed of a quarter note followed by two eighth notes, and the other composed of a dotted eighth note followed by two eighth notes. In both patterns, the nominal durations of the inter-onset intervals (IOIs) are categorically different, but in the first pattern the long duration is the sum of the two short ones, and so this rhythm can be (and most likely will be) construed in the context of a meter composed of isochronous beat periods, such as 2/4 time. The second pattern cannot fit into a similarly isochronous meter because its nominal IOI durations exhibit a 3:2:2 relationship. Even though the underpinning subdivisions (16th notes) are isochronous, and the highest level of periodicity is isochronous (the pattern repeats every seven 8th notes), the middle level is not. Its metric construal—hearing the pattern as a series of uneven beats—requires a complex meter such as 7/8 time (London, 1995).

Uneven rhythms, while well-known in the musical (and especially ethnomusicological) literature, have received relatively little empirical study regarding their production and/or perception. One recent exception is Magill and Pressing's (1997) investigation of rhythms produced by an African master drummer, which showed by means of statistical analyses that the rhythms had been generated as an additive pattern of uneven beats (considered idiomatic in West African music) rather than a series of intervals superimposed on regular subdivisions (as a Western musician might suppose). Unlike that interdisciplinary study—which concerned music of a different culture, used a single expert performer, and employed modeling of interval covariance structure—the present research is more in the tradition of rhythm production and synchronization studies in the mainstream psychological literature. Specifically, we are concerned with the challenges that uneven rhythms pose to individuals who are trained in

Music Perception VOLUME 23, ISSUE 1, PP. 61-78, ISSN 0730-7829, ELECTRONIC ISSN 1533-8312

the Western classical musical tradition, in which such rhythms are relatively rare.

Pioneering research on the production of uneven rhythmic patterns was carried out by Fraisse (1956). He requested his participants to tap spontaneously generated rhythms without repetition, thereby (perhaps deliberately) discouraging the development of metrical frameworks. Fraisse observed that long and short intervals within these rhythms tended toward a 2:1 ratio, although actually a wide range of ratios occurred, from about 1.5 to 3. The average ratio tended to be maximal at a moderate tempo and decreased as the tempo was either increased or decreased. In a later replication, Essens and Povel (1985, Exp. 1) found a much narrower range of ratios and a closer match to 2:1 for spontaneously generated rhythms, probably because the rhythms were repeated cyclically and thus induced a metrical structure that constrained the interval ratio. Tempo was not varied systematically; the tempo variations that occurred spontaneously did not seem to have any effect on the interval ratio.

Povel (1981) demonstrated that cyclically repeated rhythms are easier to reproduce when their component intervals have simple rather than complex ratios. Participants reproduced a 2:1 interval ratio quite accurately but were unable to reproduce a 3:2 ratio even when the tempo was slow enough to allow the counting of subdivisions (600 + 400 ms). The reproduced ratio approached 2:1, which implies a sharpening of the contrast between the long and short intervals. Less pronounced sharpening was observed in sequences composed of three (2:3:3), five (2:2:2:3:3), or seven intervals (2:2:3:2:3:2:3; Essens & Povel, 1985, Exp. 2), but even musically trained participants were unable to reproduce these rhythms accurately. Povel attributed this to an inability to encode the rhythms as simple hierarchical structures. Other researchers who have obtained results consistent with these findings include Sternberg, Knoll, and Zukofsky (1982), Summers, Bell, and Burns (1989), and Semjen and Ivry (2001).

In a recent study of the effect of tempo on rhythm production (Repp, Windsor, & Desain, 2002), skilled pianists played melodies notated in various two- and three-interval rhythms at four different tempi ranging from moderate to very fast. The two-interval rhythms included the uneven rhythms 2+3 and 3+2, notated in 5/8 meter. Results showed that the 2+3 rhythm was played at a ratio close to 1:2 at all tempi, whereas the 3+2 rhythm was played more accurately on average. This suggests a possible effect of the order of the intervals within the rhythmic cycle, which amounts to an effect of metrical structure (viz., of downbeat location).[1] Production of 1+2 and 2+1 rhythms, notated in 3/8 meter, was generally accurate. While tempo had little effect on the production of two-interval rhythms, it had a strong effect on the production of three-interval rhythms consisting of all possible permutations of intervals in 1:2:3 ratios, notated in either 3/4 or 6/8 meter. In those rhythms—which can be strongly syncopated but are not uneven by our definition because they can be notated in standard meters—the two longer intervals became increasingly similar in duration as the tempo increased, whereas the short interval remained proportionally stable. This progressive reduction of the 3:2 ratio in even three-interval rhythms contrasts with the seemingly tempo-invariant sharpening of the same ratio in uneven two-interval rhythms, and it led us to wonder whether and how tempo would affect the production of uneven three-interval rhythms.

We should note that, in the context of real music performance (as opposed to simple rhythm production), temporal intervals are rarely performed with the exact integer ratios suggested by notation, and this contributes to the special feeling and character of a rhythm. For example, Gabrielsson, Bengtsson, and Gabrielsson (1983) found that 2:1 and 3:1 ratios were generally reduced by musicians playing simple melodies on various instruments. Friberg and Sundström (2002) showed that the "swing ratio" of jazz drummers (nominally a 1:1 ratio) varied from 1:1 to 3:1 as a function of tempo. When two short notes are followed by a longer note, their nominal 1:1 ratio is commonly rendered as a short-long pattern, and this distortion occurs even when participants are instructed to play with mechanical accuracy (Drake & Palmer, 1993; Repp, 1999). Thus, while some deviations from nominal ratios may be intentional and serve expressive purposes, other deviations seem to be obligatory and hard to avoid, even in tasks that merely require exact production of simple rhythms.

The present study concerns such obligatory distortions of interval ratios when exact performance is intended, specifically of the 3:2 ratio in the context of uneven rhythms, where that ratio is of paramount importance. The materials included not only the 2+3 and 3+2 rhythms already studied by Repp et al. (2002), referred to as set A, but also uneven rhythms consisting of three intervals per measure, sets B (2+2+3, 2+3+2, 3+2+2) and C (2+3+3, 3+2+3, 3+3+2). The task was finger tapping rather than performance on a musical instrument.

[1]Two pianists, however, produced the 3+2 rhythm as 1+1, which contributed to the overall difference between 2+3 and 3+2.

Our study had three main purposes, which are introduced below. One was to determine the temporal limit of metrical subdivision for uneven rhythms. Another purpose was to study how tempo and metrical interpretation influence uneven rhythm production. The third purpose was to study how uneven rhythms are aligned with pacing sequences in a synchronization task.

Temporal Limits of Metrical Subdivision

The importance of mental subdivision ("counting") is often emphasized in texts on Western music performance, especially in connection with unfamiliar or complex rhythms. For example, Weisberg (1993) writes that "it is *always* necessary to keep the speed of the common unit (in the case of 5/8, the eighth note) in mind" (p. 5) and further that "musicians must develop an *inner* way of counting, one that wastes as little energy as possible. The counting must be silent and internal" (p. 6). Therefore, when an uneven rhythm such as 3+2 is to be produced with maximum accuracy, we would certainly expect musicians to employ mental subdivision (as long as the tempo permits it), even if they are not specifically instructed to do so. Somewhat surprisingly, the findings of Povel (1981) and Essens and Povel (1985), reviewed above, suggest that production of the 3:2 ratio is inaccurate (tending toward 2:1) even when counting seems possible and even when the participants are musically trained. We wondered whether we could replicate that finding.

We also wanted to determine the temporal limit of subdivision for uneven rhythms. London (2002, 2004) reviewed both the music-theoretic and psychological literature on rhythm perception and performance and concluded that the shortest IOI that can be perceived or performed as an element of a rhythmic pattern is around 100 ms. This hypothesis has found support in a recent study of sensorimotor synchronization (finger tapping) with isochronous auditory sequences (Repp, 2003), as well as in the study of jazz performance by Friberg and Sundström (2002), cited above. Thus, one might hypothesize that the shortest IOIs enabling a 3:2 ratio to be produced with mental subdivision would be multiples of 100 ms (i.e., 300 and 200 ms). However, the cognitive demands of alternating between counting 3 and 2 may well lead to an elevated subdivision limit for uneven rhythms. To determine that limit, we required participants to synchronize uneven rhythms with an isochronous sequence of rapid subdivisions. We assumed that the sequence rate at which synchronization with explicit subdivisions becomes impossible is also an estimate of the maximal rate at which mental subdivision can be accomplished.

Rhythm Production

We assessed rhythm production primarily in terms of interval ratios, with additional information provided by measures of interval variability and tapping force. As already mentioned, we wondered whether musically trained participants would distort the 3:2 ratio already at the slowest tempo, where we presumed subdivision would still be possible. Furthermore, we wanted to determine whether the produced ratio changes as the tempo is increased beyond the temporal limit of subdivision. We also examined whether rhythm production is more accurate when participants synchronize with a precise rhythm template than when they produce the rhythm freely (i.e., in a self-paced manner). In addition, we were interested in differences between and within the three rhythm sets. These differences can be characterized in terms of *temporal grouping* (or interval structure) and *metrical interpretation*, respectively.

Table 1 illustrates these distinctions. Because uneven rhythms contain unequal IOIs, they consist of temporally grouped events when they are repeated cyclically. Short IOIs function as within-group intervals; longer IOIs, as between-group intervals. It can be seen in Table 1 (where timing is rendered as spacing) that the rhythms in sets A and B form temporal groups of two and three events, respectively. In set C, the temporal grouping is ambiguous because a single event alternates with a two-event group. Assuming that a single event cannot form a group by itself, it could be regarded either as the initial or final element of a three-element group. For purposes of analysis, we assumed the second of these two options, based on the reasoning that it

TABLE 1. The three sets of rhythms. Vertical bars symbolize taps or tones; dots are silent subdivisions. Three cycles of each rhythm are shown, followed by an additional downbeat.

<table>
<tr><td>Set A</td><td></td><td></td></tr>
<tr><td>2+3</td><td>q q.</td><td>| . | . . | . | . . | . | . . |</td></tr>
<tr><td>3+2</td><td>q. q</td><td>| . . | . | . . | . | . . | . |</td></tr>
<tr><td>Set B</td><td></td><td></td></tr>
<tr><td>2+2+3</td><td>q q q.</td><td>| . | . | . . | . | . | . . | . | . | . . |</td></tr>
<tr><td>2+3+2</td><td>q q. q</td><td>| . | . . | . | . | . . | . | . | . . | . |</td></tr>
<tr><td>3+2+2</td><td>q. q q</td><td>| . . | . | . | . . | . | . | . . | . | . |</td></tr>
<tr><td>Set C</td><td></td><td></td></tr>
<tr><td>2+3+3</td><td>q q. q.</td><td>| . | . . | . . | . | . . | . . | . | . . | . . |</td></tr>
<tr><td>3+3+2</td><td>q. q q.</td><td>| . . | . | . . | . . | . | . . | . . | . | . . |</td></tr>
<tr><td>3+3+2</td><td>q. q. q</td><td>| . . | . . | . | . . | . . | . | . . | . . | . |</td></tr>
</table>

*q=quarter-note

seems more natural for the long within-group IOI to follow the short IOI. (For comments on cognitive grouping, as distinct from temporal grouping, see the General Discussion.)

The rhythms within each set differ in the location of the metrical downbeat (which, at fast tempi, may simply be *the* beat or tactus). The downbeat is the initial element of the measure or rhythm cycle, as defined in instructions and shown in quasi-musical notation in Table 1. In the schematic sequences of Table 1, downbeats are vertically aligned within each rhythm set. In set A, the downbeat can fall on either the initial (2+3) or the final (3+2) element of the temporal group. In sets B and C, the downbeat can be group-initial (2+2+3, 2+3+3), group-medial (2+3+2, 3+2+3), or group-final (3+2+2, 3+3+2). The placement of the downbeat is a cognitive act, reflecting a metrical interpretation of a constant temporal grouping structure, and we wondered whether this cognitive act would become manifest in interval ratios or other aspects of rhythm production. One might hypothesize, for example, that participants will emphasize the metrical downbeat by lengthening the subsequent inter-tap interval or by making a more forceful tap.

Although temporal grouping and metrical interpretation were varied orthogonally in our materials, they are not completely independent. It is known that, in a group of two identical tones, the second tone tends to be heard as accented (Povel & Okkerman, 1981), whereas in a group of three tones, the first and third tones are so perceived (Povel & Essens, 1985). This *grouping accent* is a major factor in beat induction from a rhythmic sequence (Lerdahl & Jackendoff, 1983; Povel & Essens, 1985). If the location of the metrical downbeat is manipulated within a fixed grouping structure by means of instructions, then in some rhythms the downbeat coincides with a grouping accent and in others it does not. The former rhythms therefore may be easier to produce than the latter. Thus, 3+2 should be easier than 2+3, 2+2+3 and 3+2+2 should be easier than 2+3+2, and 2+3+3 and 3+2+3 may be easier than 3+3+2 (if our grouping assumption is correct). Relative difficulty of production was expected to be reflected mainly in interval variability.

Regardless of metrical interpretation, temporal grouping structure was expected to have strong effects on interval variability and the relative force of taps. It is well-known that long intervals are more variable than short ones (Peters, 1989), even in mixed sequences (Repp, 1997), and taps preceded by a long inter-tap interval tend to be more forceful than those preceded by a short interval because there is more time to lift the finger (Repp & Saltzman, 2002).

Synchronization

We examined synchronization with an exact auditory rhythm template and with an isochronous sequence of downbeats. A third condition, synchronization with a rapid isochronous sequence of subdivisions, served the special purpose of determining the temporal limit of subdivision, as described earlier. The dependent variables were the tap-tone asynchronies and their variability. In synchronization with a rhythm template, possible effects of metrical interpretation were of primary interest. Our hypothesis was that the mean asynchrony associated with a particular temporal group position might be smaller and/or less variable when the metrical downbeat falls in that position. A comparison of downbeat asynchronies between the rhythm template and downbeat synchronization conditions addressed the question of whether downbeat asynchronies are sensitive to the presence or absence of metrically weak events in the pacing sequence.

Method

Participants

The 8 participants (4 women, 4 men) included 7 paid volunteers and one of the authors (B.R.).[2] All were musically trained and were also regular participants in rhythmic finger-tapping experiments. Four were professional-level classical musicians (two violists, one clarinetist, and one percussionist) and the other four were advanced amateur pianists, three with classical training and one (B.S.) who played jazz piano as well as African drums. Two of the amateurs (B.S., B.R.) were 57 years old; other participants ranged in age from 19 to 30.

Materials

The eight rhythms investigated constitute three sets (see Table 1): (A) two-interval rhythms (2+3, 3+2); (B) three-interval rhythms containing two short intervals (2+2+3, 2+3+2, 3+2+2); and (C) three-interval

[2]B.R. had previous experience with the tasks from a pilot run of the experiment, but 8 months elapsed before he ran himself again in the final version. One additional participant's data could not be used because he often tapped too lightly at fast tempi, so that many taps were not registered.

TABLE 2. **Tasks in the three sessions of the experiment. The diagrams show the transition from the synchronization to the continuation phase for the 2 + 3 rhythm.**

<table>
<tr><td colspan="3">Session I</td></tr>
<tr><td></td><td>Synchronization</td><td>Continuation</td></tr>
<tr><td>Tones</td><td colspan="2">| . | . . | . | . . | . | . . |</td></tr>
<tr><td>Taps</td><td colspan="2">| . | . . | . | . . | . | . . | . | . . | . | . . | . | . . |</td></tr>
<tr><td colspan="3">Session II</td></tr>
<tr><td></td><td>Synchronization</td><td>Continuation</td></tr>
<tr><td>Tones</td><td colspan="2">| . | . . | . | . . | . | . . | . . . . | . . . . | . . . . |</td></tr>
<tr><td>Taps</td><td colspan="2">| . | . . | . | . . | . | . . | . | . . | . | . . | . | . . |</td></tr>
<tr><td colspan="3">Session III</td></tr>
<tr><td></td><td>Synchronization</td><td>Continuation</td></tr>
<tr><td>Tones</td><td colspan="2">| . | . . | . | . . | . | . . | | | | | | | | | | | | | | | |</td></tr>
<tr><td>Taps</td><td colspan="2">| . | . . | . | . . | . | . . | . | . . | . | . . | . | . . |</td></tr>
</table>

rhythms containing two long intervals (3+3+2, 3+2+3, 2+3+3). In the analysis and description of results, the two nominally equal intervals in the three-interval rhythms will be distinguished according to whether they immediately preceded or followed the third interval during cyclic repetition: 2b (before 3) versus 2a (after 3) in set B, and 3b (before 2) versus 3a (after 2) in set C. For example, 2+2+3 = 2a+2b+3, and 2+3+3 = 2+3a+3b. The musical time signatures of the three sets, if they were notated, would have to be 5/8, 7/8, and 8/8, respectively.[3]

Each rhythm was produced at increasing tempi in three synchronization-continuation tapping tasks that differed in the nature of the continuation task, as illustrated in Table 2. During the synchronization phase of each task, participants were required to tap in synchrony with a computer-generated auditory sequence that instantiated the rhythm with mathematical accuracy (i.e., a rhythm template). Subsequently, they continued to tap the rhythm in a self-paced manner (Session I) or were paced by an isochronous series of downbeats (Session II) or by a rapid isochronous series of subdivisions (Session III). Although the continuation tasks of Sessions II and III were synchronization tasks as well, we call them continuation tasks whenever they need to be distinguished from the initial synchronization with a rhythm template that was common to Sessions I, II, and III.

All pacing sequences consisted of identical high-pitched digital piano tones (E7, about 2640 Hz), which were produced on a Roland RD-250 digital piano under control of MAX 3.0 software running on a Macintosh Quadra 660AV computer.[4] The tones had abrupt onsets and decayed freely thereafter in a roughly exponential fashion. Participants listened over Sennheiser HD540 II headphones at a comfortable intensity. In Session I, each trial consisted of 15 cycles of a particular rhythm template plus one extra tone (downbeat) at the end, followed by a silent continuation period equivalent to the duration of 29 cycles; a single tone signaled the end of that period. In Session II, each trial began likewise with 15 cycles of a rhythm template and then continued with 30 tones marking cycle beginnings (downbeats). In Session III, each trial began with 7 cycles of a rhythm template and then continued with rapid isochronous subdivision beats for the equivalent of 20 pattern cycles. Because the task of Session III served a different purpose (the determination of the subdivision limit), the abbreviated synchronization condition only served to induce the rhythm; the data from that condition were not analyzed.

For each rhythm in each session, there were eight successive trials differing in tempo. Tempo was defined in terms of the duration of (implicit or explicit) subdivisions, referred to here as *metrical grid spacing* (MGS), which decreased from 170 ms in the first trial to 100 ms in the eighth trial, in steps of −10 ms. For example, the interval durations for the 2+3+2 pattern with MGS = 140 ms were 280, 420, and 280 ms, and the cycle duration was 980 ms. The cycle durations of the rhythms in the three sets were 5*MGS, 7*MGS, and 8*MGS, respectively. The range of MGS values was selected by author B.R. on the basis of his impression during a pilot run that mental subdivision was possible at 170 ms but clearly impossible at 100 ms.

Procedure

The three sessions were typically one week apart and lasted a good hour (I, II) or less than an hour (III).

[3]The rhythms in 8/8 meter could be construed as syncopated rhythms within an even 4/4 metrical framework. We found it unlikely, however, that this interpretation would be adopted by participants in our experiment because it is cognitively much more demanding than an uneven meter.

[4]Due to a peculiarity of this setup, the tempo of the output was about 2.4% faster than specified in the MIDI instructions, as had been determined in earlier acoustic waveform measurements. The participants' finger taps were registered at a correspondingly slower rate. Throughout this article, all millisecond values are reported as they appeared in the MAX environment. Apart from the constant scaling factor of .976, MAX was highly accurate (within 1 ms) in timing the sequences and registering the finger taps.

Within each session, the three rhythm sets were performed in the order A, B, C. The order of the rhythms within each set varied across participants but was the same in each session for each participant.

At the beginning of each session, the participant read written instructions containing illustrations like those in Tables 1 and 2, and he or she was given a few sample trials. Each rhythm to be produced was announced by the experimenter and was pointed to on the instruction sheet; participants had time to try out each rhythm informally before starting a series of trials. In Session I, each trial required synchronization of taps with an auditory rhythm template, starting with the third downbeat in the sequence (i.e., the fifth tone for rhythm set A, the seventh tone for sets B and C), and continuation of the rhythm after the sequence ended, without interruption and at the same tempo, until a single tone sounded (*self-paced continuation*). In Session II, the task was similar, except that during continuation of the rhythm each downbeat tap had to be synchronized with a tone (*downbeat-paced continuation*). The downbeat tap was defined as the one that started each cycle of a rhythm (see Table 1). In Session III, after the abbreviated initial synchronization phase, each tap had to be synchronized with a subdivision tone (*subdivision-paced continuation*). Participants were told that, if they could not synchronize with the appropriate subdivision tones, they should ignore them and simply tap the rhythm as regularly as possible until the subdivision sequence ended.

Participants sat in front of a computer monitor that displayed the trial number. The first trial in a block of eight trials for a given rhythm was started by clicking a button with the mouse, and each subsequent trial was started by the participant pressing the space bar of the computer keyboard. If a participant started tapping at the wrong time or was unhappy with his or her performance on a trial, the trial was repeated, but such repetitions were infrequent. There were short breaks between blocks of trials. Participants tapped with the preferred (right) hand on a Roland SPD-6 electronic percussion pad, which they held on their lap. The sound output of the percussion pad was not used, but there was direct auditory feedback from the taps (a thud), in proportion to the tapping force. The two percussionists chose to tap forcefully "from above" using the middle finger, whereas other participants tapped more gently with the index finger and typically rested their palm and other fingers on the pad while tapping. The taps were registered by the percussion pad (set to "manual" sensitivity) and were transmitted as MIDI information to the computer.

Data Analysis

At fast tempi, it sometimes happened that some taps were too weak to be registered electronically. These occasional gaps in the data were corrected by realigning the registered taps when computing asynchronies and by deleting inter-tap intervals that spanned a gap. The gaps were generally not a problem for computation of means and standard deviations. In some instances, however, they were so frequent and/or the produced rhythm was so distorted that the trial was considered a failure to execute the required task. Such trials were deleted, as were rare trials that exhibited phase slips or continuous phase drift in the downbeat-paced continuation phase of Session II. (Trials exhibiting phase drift in Session III were not excluded; see below.) There were no categorical mistakes in rhythm production, nor were there any failures to synchronize with the rhythm template during the synchronization phases of Sessions I and II. The total number of trials excluded from analysis was 29 (1.9%), nearly all of them at the fastest tempi.

For the analysis of rhythm production, mean inter-tap interval durations and standard deviations were computed across all intact cycles of each rhythm in each trial, separately for the synchronization and continuation conditions in Sessions I and II, and also for the continuation condition in Session III. Interval ratios were computed from the mean interval durations of each trial by dividing the duration of a long ("3") interval by that of a short ("2") interval, so that the nominal (expected) ratio was 1.5 in all cases. For the rhythms in set A, there was just one ratio (3/2); for each of the other two rhythm sets, there were two ratios (set B: 3/2a and 3/2b; set C: 3a/2 and 3b/2). The data from Sessions I and II were subjected to separate repeated-measures ANOVAs for each rhythm set, with the variables of ratio (2 levels, for sets B and C only), rhythm (2 levels in set A, 3 levels in sets B and C), session (2 levels), condition (2 levels: synchronization vs. continuation), and tempo (8 levels). Missing cells due to excluded trials were filled in by duplicating the value(s) of the most appropriate adjacent cells in the design. The continuation data from Session III were analyzed together with the continuation data from Sessions I and II in a second set of ANOVAs, whose results will be mentioned only if they are of special interest.

For the analysis of synchronization with a rhythm template (Sessions I and II), asynchronies were computed by subtracting the pacing sequence tone onset times from the tap registration times. Thus, a negative asynchrony indicates that the tap preceded the tone.

Mean asynchronies and standard deviations were computed across rhythm cycles and analyzed in separate repeated-measures ANOVAs for each rhythm set, with the variables of position (2 or 3 levels), rhythm (2 or 3 levels), session (2 levels), and tempo (8 levels). Position was defined with respect to the temporal grouping structure of a rhythm set and was independent of downbeat location, which was represented by the rhythm variable. The asynchronies of the downbeat-paced continuation condition in Session II were analyzed separately together with the downbeat asynchronies extracted from the synchronization condition of Session II. The asynchronies of the subdivision-paced continuation tapping in Session III were not analyzed in detail.

In addition to these temporal measurements, MIDI velocities (range: 0–127) were obtained as a rough measure of tapping force. One participant, the professional percussionist, tapped so strongly that the MIDI velocity was usually at its maximum; his data had to be excluded from analysis. Only the MIDI velocities from Session I were analyzed, in ANOVAs similar to those on asynchronies.

In order not to clutter the text too much, ANOVA results are not reported exhaustively. Statistics are omitted for effects so large that their significance is obvious, as well as for duplicate results and for minor effects that are of little theoretical interest. Although the Greenhouse-Geisser or Huyhn-Feldt correction is recommended for repeated-measures effects with more than one degree of freedom, the computer program used did not provide either of these corrections. To compensate for this, multiple-degrees-of-freedom effects were considered significant only if $p < .01$.

Results

Temporal Limits of Metrical Subdivision

The purpose of the subdivision-paced continuation condition of Session III was to provide an estimate of the temporal limit of metrical subdivision for uneven rhythms, a limit that presumably also applies to mental subdivision when subdivisions are not physically present. Failures to synchronize were apparent as phase drift relative to the pacing sequence during part or all of the continuation tapping. A trial was considered successful if the standard deviation of the downbeat asynchronies, calculated relative to the theoretical downbeat in the pacing sequence, was less than 50 ms. Trials with larger variability were considered unsuccessful. This criterion was arbitrary, but it distinguished well between trials that exhibited phase drift (which is easy to detect by eye in a series of numerical asynchrony values) and those that did not. Borderline cases (e.g., where phase drift started near the end of a trial) were rare.

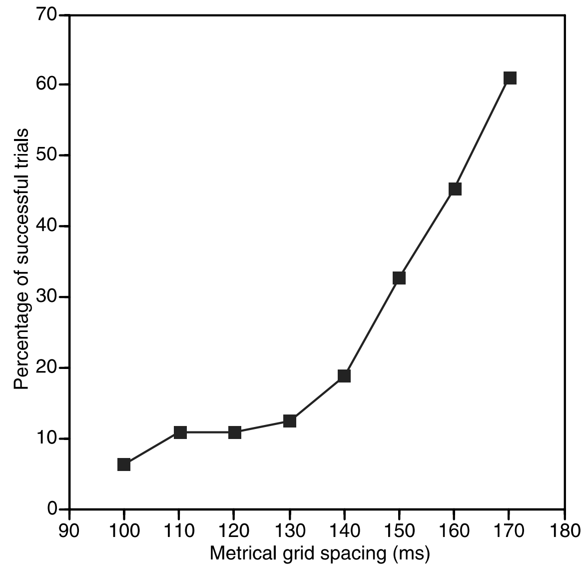

FIG 1. Percentage of successful trials in the subdivision-paced continuation condition of Session III as a function of metrical grid spacing.

Figure 1 shows the mean percentage of successful trials as a function of MGS duration. The range of tempi (MGS durations) had been chosen with the expectation that synchronization with a rapid stream of subdivisions would be possible at the slowest tempo, but participants found the task somewhat more difficult than expected. On average, synchronization was successful only about 60% of the time at the slowest tempo, and the percentage decreased rapidly as the tempo increased. If the 50% crossover point is taken as an estimate of the mean "synchronization threshold," then the estimate is 163 ms, which is considerably higher than a previous estimate of 123 ms for tapping with every fourth tone of an isochronous sequence (Repp, 2003). This suggests that the temporal limit of subdivision increases with the complexity of the rhythm.

Individual synchronization thresholds ranged from 143 ms (for the professional percussionist) to above 170 ms (for the participant with the least musical training). The large majority of unsuccessful trials exhibited a slowing down of tapping relative to the pacing sequence, resulting in increasingly large positive asynchronies. Only one participant had about equal numbers of unsuccessful trials showing slowing down and speeding up.

The data also suggested some differences among rhythms, although these data were too sparse for statistical significance tests. Synchronization success was lower for 3+2 than for 2+3, lower for 2+3+2 than for 2+2+3 and 3+2+2, and lower for 3+2+3 than for 3+3+2 and 2+3+3. The differences among the three-interval rhythms in sets B and C are in accord with the prediction that rhythms whose downbeat does not coincide with a grouping accent should be more difficult to execute. The difference in set A, however, is contrary to this prediction.

In summary, the results of this part of our study suggest that, within the range of chosen tempi, subdivision of uneven rhythms into elementary metrical pulses was difficult to begin with and became impossible as the tempo increased. Except for the initial difficulty, which was greater than expected, this was the situation we had intended to create for our examination of rhythm production and synchronization.

Rhythm Production

INTERVAL RATIOS

The three main questions regarding interval ratios were as follows: (a) What ratio do participants start out with at the slowest tempo? (b) How does the ratio change as the tempo is increased? (c) Does metrical downbeat location have any effect on the interval ratio? We address these questions for each rhythm set in turn.

For the two-interval rhythms in set A, Repp et al. (2002) had found that the interval ratio was sharpened considerably (i.e., greater than 1.5) even at a slow tempo and did not change significantly as the tempo increased. This finding was basically replicated: The mean interval ratio for set A rhythms in Sessions I and II was 1.76, and the main effect of tempo was nonsignificant, as were all interactions involving tempo. However, closer inspection of the data revealed considerable individual differences, which are summarized in Table 3. The significance of individual changes in interval ratio was determined by computing the correlation between interval ratio and MGS duration across 2 (rhythms) × 8 (tempi) × 5 (conditions) = 80 data points for each participant, where the conditions include synchronization in Sessions I and II and continuation in Sessions I–III. For three participants, mean interval ratio increased significantly as MSG duration decreased (a negative correlation), whereas for three others the ratio decreased (a positive correlation); two showed no significant change.

The main effect of rhythm (2+3 vs. 3+2) was nonsignificant in set A; thus, there was no overall effect of metrical interpretation (downbeat location) on the interval ratio. Furthermore, there was no overall difference between synchronization and continuation: Synchronization with a precise rhythm template did not make the produced interval ratios more precise. There was an interaction, however: For 2+3 the mean ratio was larger during synchronization than during continuation, whereas this was not the case for 3+2, $F(1,7) = 26.8$, $p < .001$. The mean ratio was also higher in Session I (1.80) than in Session II (1.72), $F(1,7) = 7.4$, $p < .03$, and was even lower in the continuation condition of Session III (1.65). This could reflect an effect of practice. The decrease between Sessions I and II was larger for 2+3 than for 3+2, $F(1,7) = 7.2$, $p < .04$.

TABLE 3. Mean interval ratios (intercepts of regression line relating interval ratio to MGS duration) for set A rhythms at the slowest (MGS = 170 ms) and fastest (MGS = 100 ms) tempi, and correlation (d.f. = 78) between ratios and MGS duration for individual participants.

Participant	MGS = 170 ms	MGS = 100 ms	Correlation	*p*<
B.S.	1.76	2.08	−.55	.001
B.R.	1.45	1.92	−.76	.001
H.R.	1.83	1.72	.26	.05
R.F.	1.60	1.59	.03	n.s.
R.B.	1.67	1.81	−.45	.001
S.L.	1.75	1.82	−.09	n.s.
S.K.	1.82	1.65	.35	.01
V.T.	1.71	1.64	.24	.05

Each of the three rhythms in set B yielded two ratios, 3/2a and 3/2b. The mean ratio was 1.73, which indicates substantial enhancement of the contrast between long and short intervals. The mean 3/2a ratio (1.77) was larger than the mean 3/2b ratio (1.69), $F(1,7) = 9.9$, $p < .02$. This implies that the second within-group interval (2b, which preceded the long between-group interval) was longer than the first within-group interval (2a)—a form of group-final lengthening (Drake & Palmer, 1993).

In contrast to the results for set A, the mean ratio in set B increased significantly from 1.67 to 1.83 as the tempo increased, $F(7,49) = 5.2$, $p < .0002$. However, there were again individual differences, with some participants showing significant increases in both ratios as the tempo increased, others showing a significant increase in the 3/2a ratio but not in the 3/2b ratio, and yet others showing no significant change with tempo of either ratio (see Table 4). The effect of tempo was somewhat larger during synchronization than during continuation, $F(7,49) = 3.7$, $p < .003$. There were no

TABLE 4. Mean interval ratios (intercepts of regression line) for set B rhythms at the slowest (MGS = 170 ms) and fastest (MGS = 100 ms) tempi, and correlation (d.f. = 78) between ratios and MGS duration for individual participants.

Ptcpt	Ratio	MGS = 170 ms	MGS = 100 ms	Correlation	*p*<
B.S.	3/2a	1.46	1.80	−.26	.05
	3/2b	1.52	1.78	−.33	.01
B.R.	3/2a	1.64	1.80	−.46	.001
	3/2b	1.63	1.65	−.13	n.s.
H.R.	3/2a	1.88	1.82	.09	n.s.
	3/2b	1.74	1.73	.03	n.s.
R.F.	3/2a	1.76	1.82	−.34	.01
	3/2b	1.63	1.71	−.25	.05
R.B.	3/2a	1.40	1.78	−.64	.001
	3/2b	1.47	1.72	−.61	.001
S.L.	3/2a	1.34	1.89	−.65	.001
	3/2b	1.52	1.75	−.54	.001
S.K.	3/2a	1.77	1.76	.02	n.s.
	3/2b	1.72	1.79	−.16	n.s.
V.T.	3/2a	1.72	2.01	−.61	.001
	3/2b	1.71	1.71	.01	n.s.

TABLE 5. Mean interval ratios (intercepts of regression line) for set C rhythms at the slowest (MGS = 170 ms) and fastest (MGS = 100 ms) tempi, and correlation (d.f. = 78) between ratios and MGS duration for individual participants.

Ptcpt	Ratio	MGS = 170 ms	MGS = 100 ms	Correlation	*p*<
B.S.	3a/2	1.27	1.80	−.62	.001
	3b/2	1.20	2.44	−.72	.001
B.R.	3a/2	1.43	1.74	−.69	.001
	3b/2	1.56	1.81	−.65	.001
H.R.	3a/2	1.58	1.69	−.16	n.s.
	3b/2	1.61	1.79	−.22	.05
R.F.	3a/2	1.73	1.78	−.09	n.s.
	3b/2	1.74	1.93	−.30	.01
R.B.	3a/2	1.30	1.70	−.49	.001
	3b/2	1.28	1.83	−.53	.001
S.L.	3a/2	1.25	1.62	−.57	.001
	3b/2	1.26	1.77	−.64	.001
S.K.	3a/2	1.45	1.72	−.36	.001
	3b/2	1.44	1.63	−.23	.05
V.T.	3a/2	1.45	1.55	−.23	.05
	3b/2	1.44	1.79	−.49	.001

significant effects involving rhythm (2+2+3 vs. 2+3+2 vs. 3+2+2), which means that metrical interpretation had no consistent effect on timing.

An ANOVA conducted on the set B interval ratios in continuation tapping (data from all three sessions) did not show a significant difference between the 3/2a and 3/2b ratios but instead a very reliable Ratio × Tempo interaction, $F(7,49) = 5.6$, $p < .0001$: The 3/2a ratio increased more with tempo than did the 3/2b ratio, which means that the relative lengthening of the final within-group interval (2a < 2b) emerged as the tempo increased. In addition, the analysis showed that the mean interval ratio in continuation tapping tended to decrease across the three sessions, $F(2,14) = 4.2$, $p < .04$, and that this decrease was more pronounced for the 3/2a ratio than for the 3/2b ratio, $F(2,14) = 10.0$, $p < .002$, especially at a slow tempo, $F(7,49) = 2.4$, $p < .007$. This could reflect again an effect of practice.

Each of the rhythms in set C also yielded two ratios, 3a/2 and 3b/2. The mean ratio of 1.64 was somewhat closer to the target value of 1.5 than in the other two rhythm sets. As can be seen in Table 5, only two participants started out with ratios greater than 1.5; most others actually started with ratios smaller than 1.5. The mean 3a/2 ratio (1.59) was smaller than the mean 3b/2 ratio (1.69), $F(1,7) = 6.1$, $p < .05$, which means that 3a < 3b. This supports our assumption that 3b functioned as the between-group interval in these rhythms. The ratios decreased from Session I to Session II, $F(1,7) = 13.9$, $p < .008$, but this decrease was smaller for 3a/2 than for 3b/2, $F(1,7) = 8.9$, $p < .02$. Ratios were also smaller in synchronization (1.62) than in continuation (1.67), $F(1,7) = 12.5$, $p < .01$, and a significant triple interaction, $F(1,7) = 8.1$, $p < .03$, suggested that this difference was largest for 3b/2 in Session I. Most importantly, the mean ratio increased significantly with tempo (from 1.48 to 1.88), $F(7,49) = 9.5$, $p < .0001$, but this increase tended to be smaller for 3a/2 than for 3b/2, $F(7,49) = 3.0$, $p < .02$. The effect of tempo on the interval ratios was also significant at the individual level; only two individuals failed to show a significant increase of the 3a/2 ratio (Table 5). As in set B, there were no significant effects involving rhythm (3+3+2 vs. 3+2+3 vs. 2+3+3), which indicates that metrical downbeat location did not play any role.

The main results of this section are that (a) the long/short interval ratios were already enhanced at the slowest tempo in rhythm sets A and B; (b) they increased as the tempo increased in sets B and C; and (c) downbeat location within each rhythm set had no influence on interval ratios.

INTERVAL VARIABILITY

The standard deviations of the inter-tap interval durations provided additional data that were of interest with regard to possible effects of metrical interpretation.

ANOVAs on these data had the variable of interval (2 levels for set A, 3 levels for sets B and C) in lieu of ratio.

Three main effects were shown by all three rhythm sets and were significant in each instance: First, as had been fully expected on the basis of earlier interval production studies (e.g., Peters, 1989; Repp, 1997), the long "3" intervals exhibited greater variability than the short "2" intervals. Second, variability decreased as the tempo increased (i.e., as all intervals got shorter). Interestingly, this decrease was especially pronounced in the continuation phase of Session III. Clearly, participants' inability to synchronize with rapid subdivisions did not prevent them from producing the rhythms consistently. Third, variability was higher during continuation than during synchronization. In addition, it was noted that variability of both long and short intervals was somewhat higher in set C than in sets A and B.

With regard to metrical interpretation (the rhythm variable in the ANOVA), some weak effects were found in sets A and C, but not in set B. In set A, interval variability was somewhat higher for 2+3 than for 3+2, $F(1,7) = 8.5$, $p < .03$, and this difference was larger during continuation than during synchronization, $F(1,7) = 6.2$, $p < .05$. In Session II, the difference was present for both intervals, but in Session I it held only for the long interval, $F(1,7) = 12.0$, $p < .01$. In set C, the Rhythm × Interval × Tempo interaction approached significance in the main ANOVA, $F(28,196) = 1.7$, $p < .02$, and reached significance in the ANOVA on the continuation data from all three sessions, $F(28,196) = 1.8$, $p < .01$: At the slower tempi, variability of the long intervals was greater in 3+2+3 than in 2+3+3 and 3+3+2, but this difference went away as the tempo increased. Clearly, metrical interpretation had much weaker and less consistent effects on interval variability than did interval duration, tempo, and tapping mode (synchronization vs. continuation).

TAPPING FORCE

Tapping force (MIDI velocity) was another aspect of the data that was of interest because of potential metrical effects. In particular, our hypothesis was that taps in the same group position might be executed with greater force when they represent metrical downbeats than when they are metrically weak. In addition, we expected to find effects of group position, such that taps following long intervals are more forceful than those following short intervals. In the ANOVAs, group position replaced interval as a variable, and the session variable disappeared because only the MIDI velocities from Session I were analyzed.

The effects of temporal grouping and of metrical interpretation are presented graphically in Figure 2. In rhythm set A (Figure 2A), group-initial taps (which followed the long interval) were stronger than group-final taps, as predicted, $F(1,6) = 21.1$, $p < .004$, and this difference increased as the tempo increased, $F(7,42) = 10.2$, $p < .0001$. The difference was also larger in the 2+3 rhythm, where the group-initial tap represented the metrical downbeat, than in the 3+2 rhythm, where

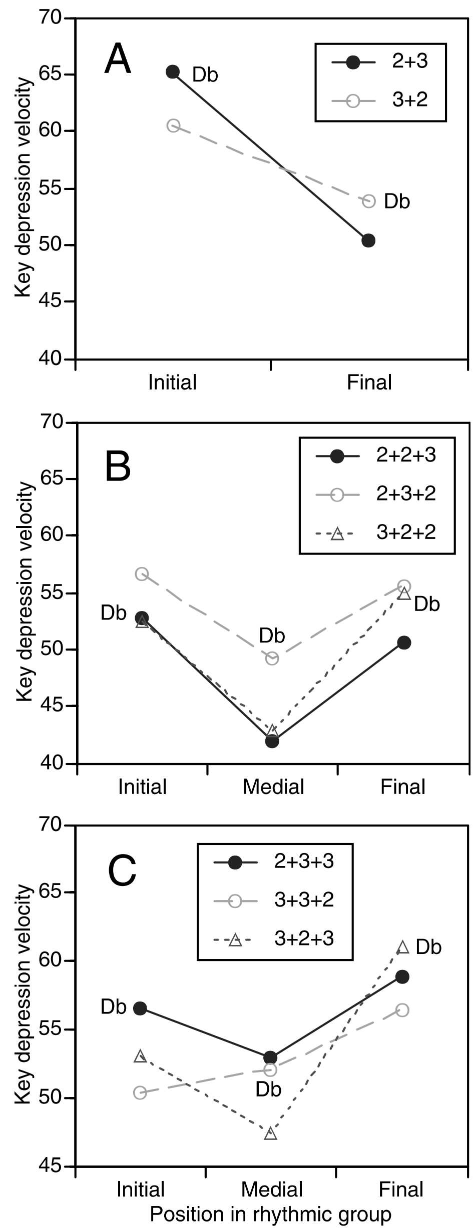

FIG 2. Mean key depression velocities for the different rhythms in Session I as a function of rhythmic group position. "Db" indicates metrical downbeats.

the group-final tap represented the downbeat, $F(1,6) = 22.8$, $p < .004$. This means that the metrical accent (i.e., the cognitively imposed downbeat) increased the relative force of the associated tap, as predicted.

In rhythm set B (Figure 2B), taps were weaker when they occurred in group-medial position (preceding and following a short interval) than when they were group-initial or group-final, $F(2,12) = 16.4$, $p < .0005$. The group-initial tap (following a long interval) was weaker than the group-final tap (following a short interval) at slow tempi, but it became stronger than the group-final tap as the tempo increased, $F(14,84) = 3.9$, $p < .0001$, which is the predicted difference. The Rhythm × Position interaction was not significant, $F(4,24) = 1.0$, $p = .42$. Thus, there was no effect of metrical interpretation here, only of temporal grouping, although Figure 2B reveals a small tendency for the downbeats to be relatively more forceful.

In rhythm set C (Figure 2C), the weakest tap on average was the one following the short interval (considered group-medial), whereas the strongest tap was the one both preceding and following a long interval (considered group-final). These position effects emerged gradually as the tempo increased, $F(14,84) = 4.0$, $p < .0001$. As in rhythm set A, metrical accents made taps relatively more forceful, $F(4,24) = 4.3$, $p < .01$, although this effect was small compared to that of group position. Thus, there were some reliable effects of metrical interpretation here, which is reassuring in that they indicate that participants interpreted the rhythms according to instructions.

An unexpected difference that was significant for all three rhythm sets was that participants tapped more strongly during synchronization than during self-paced continuation (Session I). This could represent increasing fatigue in the course of each trial, or greater muscular tension when trying to synchronize with a rhythm template than when tapping in a self-paced manner. Tapping force also decreased substantially as the tempo increased, which may likewise include a fatigue component but probably reflects mainly a reduction in movement amplitude due to the shorter inter-tap intervals.

Synchronization

ASYNCHRONIES WITH RHYTHM TEMPLATES

The fact that interval ratios were not produced accurately implies substantial asynchronies in synchronization with a rhythm template. The asynchronies were necessarily different for taps in different group positions, so a significant main effect of position in an ANOVA is trivial. The main question of interest was whether asynchronies are reduced when a tap in a given group position represents the metrical downbeat, compared to when it does not. In an ANOVA, this would be reflected in a significant Rhythm × Position interaction.

The effects of group position and metrical interpretation on the mean asynchronies are shown in Figure 3. In rhythm set A (Figure 3A), the mean asynchrony of the group-initial tap was 9.5 ms, whereas that of the

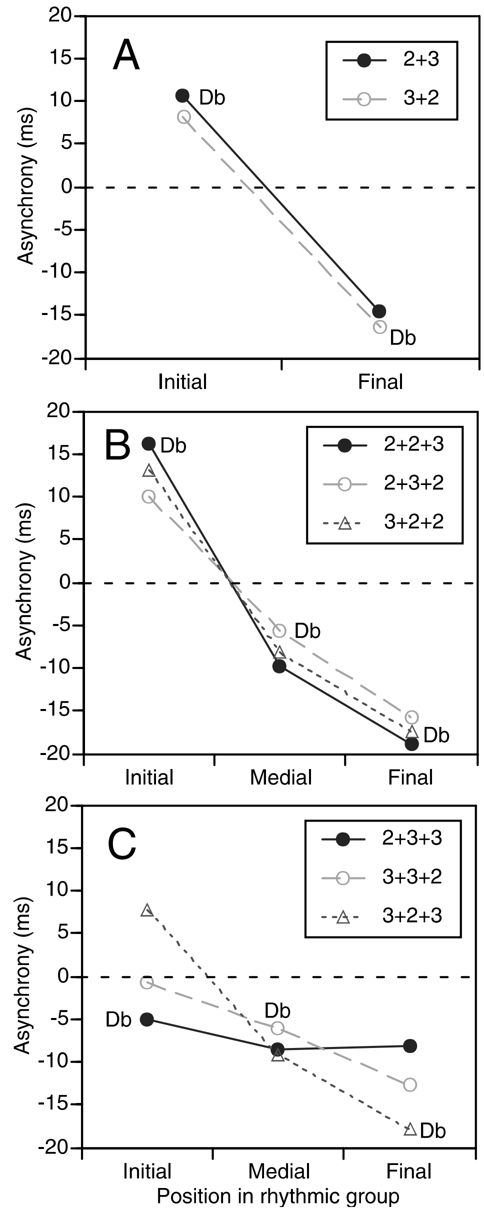

FIG 3. Mean asynchronies for the different rhythms in the synchronization conditions of Sessions I and II, as a function of rhythmic group position. "Db" indicates metrical downbeats.

group-final tap was −15.5 ms, $F(1,7) = 72.2$, $p < .0001$. These values reflect the relative contraction of the short within-group interval and the relative expansion of the long between-group interval, as well as a slight negative asynchrony overall. The Rhythm × Position interaction was far from significance, which indicates that metrical interpretation had no reliable effect. No other effects reached significance.

In rhythm set B (Figure 3B), the mean asynchronies were 13.1 ms for the group-initial tap, −7.9 ms for the group-medial tap, and −17.3 ms for the group-final tap, $F(2,14) = 30.5$, $p < .0001$. Here there was also a significant main effect of tempo, $F(7,49) = 6.6$, $p < .0001$: Overall, the mean asynchrony became less negative as the tempo increased, changing from −12.0 to 1.4 ms. The Rhythm × Position interaction was not significant, $F(4,28) = 1.9$, $p < .15$. Although the Rhythm × Position × Tempo interaction was reliable, $F(28,196) = 2.5$, $p < .0001$, it was difficult to interpret.

In rhythm set C (Figure 3C), the mean asynchrony also became less negative as tempo increased, $F(7,49) = 14.5$, $p < .0001$, changing from −19.0 to 2.3 ms. The main effect of position did not reach significance here, but the Position × Tempo interaction did, $F(14,98) = 5.3$, $p < .0001$. The asynchrony of the group-initial tap (preceding the short interval) changed much more with tempo than did the group-medial and group-final asynchronies: from −25.0, −16.2, and −15.9 ms to 22.0, −8.4, and −6.7 ms, respectively. There was also a Session × Position interaction, $F(2,14) = 14.8$, $p < .0005$, because the effect of position was larger in Session I than in Session II. The Rhythm × Position interaction approached significance, $F(4,28) = 3.5$, $p < .02$, but it did not reflect smaller asynchronies for downbeats. Rather, the asynchronies in the initial and final group positions were more negative when the downbeat fell in these positions.

These results offer no support for our hypothesis that downbeats would be associated with smaller asynchronies. Rather, participants' strategy seemed to be to minimize the mean asynchrony of each rhythm cycle.

VARIABILITY OF ASYNCHRONIES WITH RHYTHM TEMPLATES

Variability of asynchronies decreased significantly as a function of increasing tempo in all three rhythm sets. The question of primary interest was whether this variability would be reduced when taps function as metrical downbeats. This would again be reflected in the Rhythm × Position interaction.

The results are shown in Figure 4. In rhythm set A (Figure 4A), variability was marginally greater for 2+3 than for 3+2, $F(1,7) = 6.1$, $p < .05$. The main effect of position was not significant, nor was the Rhythm × Position interaction.

In rhythm set B (Figure 4B), variability was greater in the group-initial position than in the medial and final positions, $F(2,14) = 16.8$, $p < .0002$. This may reflect an effect of the long (most variable) interval preceding the group-initial position. However, this difference was present only at the slower tempi; it disappeared as the tempo increased, $F(14,98) = 4.5$, $p < .0001$. Overall,

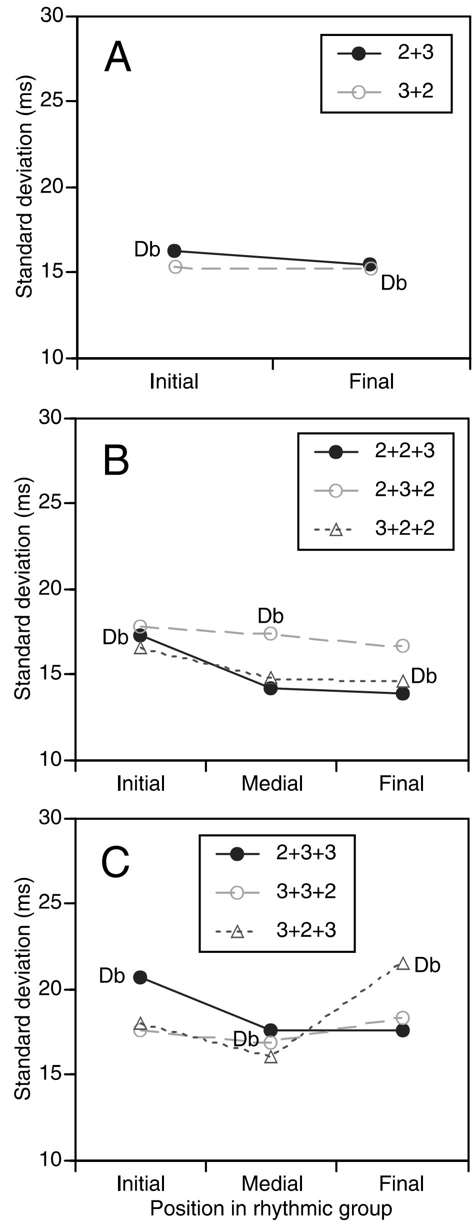

FIG 4. Mean standard deviations of asynchronies for the different rhythms in the synchronization conditions of Sessions I and II, as a function of rhythmic group position. "Db" indicates metrical downbeats.

variability was higher for 2+3+2 than for 2+2+3 and 3+2+2, $F(2,14) = 7.2$, $p < .008$, which is in agreement with the greater predicted difficulty of the 2+3+2 rhythm. The Rhythm × Position interaction was also significant, $F(4,28) = 4.2$, $p < .009$, because the effect of position was nearly absent when the downbeat was in group-medial position (2+3+2). The direction of this difference is contrary to the hypothesis of reduced variability in the downbeat position.

In rhythm set C (Figure 4C), variability was greater than in the other two rhythm sets (as was the case with interval variability). Variability was smaller in the assumed group-medial position than in the initial and final positions, $F(2,14) = 8.5$, $p < .004$. This could again reflect an effect of preceding interval duration, because the group-medial tap was preceded by the short (least variable) interval. The Rhythm × Position interaction was significant, $F(4,28) = 6.4$, $p < .0008$, but again contrary to expectations: In the initial and final positions, the metrical accent *increased* the variability.

Thus, downbeats were associated neither with smaller asynchronies nor with reduced variability. The variability of asynchronies depended much more on group position (specifically, on the duration of the preceding interval) than on metrical interpretation.

ASYNCHRONIES IN DOWNBEAT-PACED CONTINUATION TAPPING

The asynchronies obtained in the downbeat-paced continuation condition of Session II (which naturally were associated only with downbeat taps) were analyzed together with the downbeat asynchronies extracted from the (rhythm-template-paced) synchronization condition of the same session, to determine whether the absence of metrically weak pacing tones in the downbeat-paced condition had any effect on the alignment of downbeat taps with their pacing tones. Such an effect would be reflected in a Condition × Rhythm interaction in an ANOVA. The results are shown in Figure 5.

The Condition × Rhythm interaction was significant for rhythm sets A, $F(1,7) = 74.3$, $p < .0001$, and B, $F(2,14) = 24.4$, $p < .0001$, but not for set C. During synchronization with a rhythm template, mean downbeat asynchronies in set A were positive for 2+3 (group-initial downbeat) but negative for 3+2 (group-final downbeat), whereas during downbeat-paced continuation the difference was reversed (Figure 5A). Similarly, downbeat asynchronies in set B were positive for 2+2+3 (group-initial downbeat), slightly negative for 2+3+2 (group-medial downbeat), and strongly negative for 3+2+2 (group-final downbeat) during rhythm-template synchronization, but they showed a reversed pattern during downbeat-paced continuation (Figure 5B). Set C rhythms also showed differences, although they were not significant; in particular, 3+2+3 showed a large negative downbeat asynchrony (group-medial downbeat) during synchronization with a rhythm template, but a much smaller asynchrony during downbeat-paced continuation (Figure 5C). These differences indicate that the presence or absence of pacing tones on metrically weak beats had strong effects on the alignment of the downbeat tap with its pacing tone. This is consistent with a synchronization

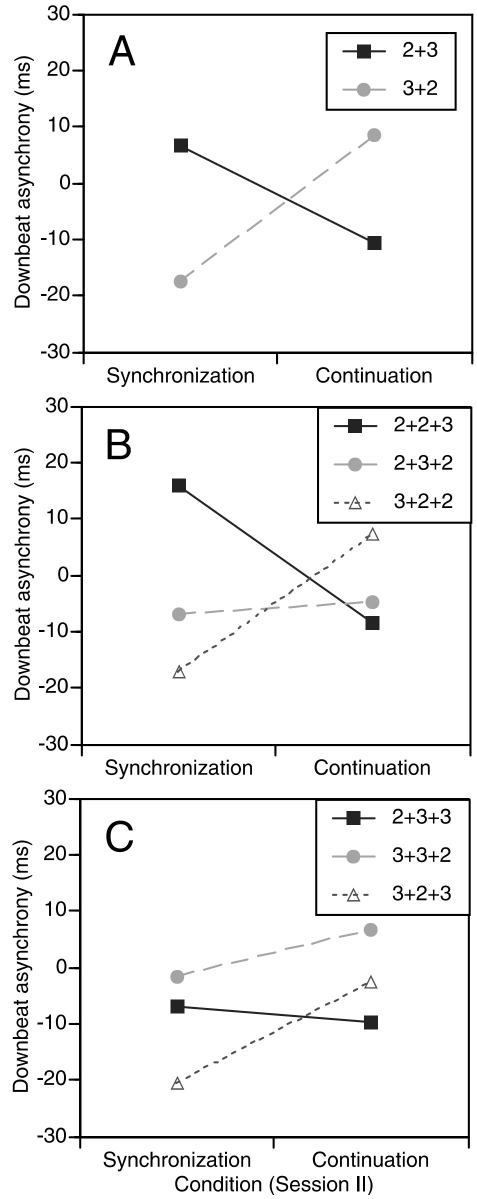

FIG 5. Mean downbeat asynchronies for the different rhythms during the synchronization and downbeat-paced continuation conditions of Session II.

strategy that aims to minimize the mean asynchrony per rhythm cycle.

VARIABILITY OF DOWNBEAT-PACED ASYNCHRONIES

The standard deviations of the downbeat asynchronies in Session II were also analyzed. Variability decreased as tempo increased for all rhythms. The rhythms within set A did not differ in variability, but in set B the 2+3+2 rhythm was more variable than the other two rhythms, as predicted, $F(2,14) = 4.7, p < .03$, especially during downbeat-paced continuation, $F(2,14) = 4.2$, $p < .04$. In set C, however, variability increased from 3+3+2 to 3+2+3 to 2+3+3, $F(2,14) = 12.0, p < .001$, which was unexpected. The most striking finding here was that the variability of downbeat asynchronies was much larger in downbeat-paced continuation than in synchronization with a complete rhythm template: 23.0 vs. 15.9 ms for set A, 28.1 vs. 16.3 ms for set B, and 34.9 vs. 19.6 ms for set C, all differences being highly significant. Thus, it was much harder to stay in synchrony with downbeat tones when there were no pacing tones for the metrically weak beats.

Discussion

Temporal Limits of Metrical Subdivision

One purpose of our study was to determine the temporal limit of metrical subdivision for uneven rhythms and thereby to verify that the range of tempi chosen made it difficult or impossible to engage in mental subdivision. In the subdivision-paced continuation condition of Session III, we found that participants were unable to synchronize the uneven rhythms with a rapid stream of isochronous pulses when the MGS was less than 163 ms, on average, and less than about 145 ms for the most skilled participants. Repp (2003) had previously found that the limit for tapping with every fourth tone in such a rapid sequence (i.e., tapping isochronous beats with quadruple subdivision) was 123 ms on average and as low as 100 ms in some individual cases. Although the criteria for determining lack of synchronization were not exactly the same in the two studies,[5] they can hardly explain the large difference, which suggests that rhythmic complexity has a strong impact on the temporal limit of subdivision. Presumably, the cognitive demands of alternating between counting 2 and 3 consume attentional resources that are needed for the perceptual tracking of a rapid stimulus sequence and/or for the processing of sensory feedback about the synchronization error.

We have been assuming that the temporal limit of synchronization also applies to mental subdivision in the absence of an explicit pulse stream. Although mental subdivision may involve generation of imaginary nonverbal (auditory or motor) events, and not necessarily covert verbal counting such as "one-two-one-two-three," the mean synchronization threshold for uneven rhythms is close to the temporal limit for overt or covert verbal counting, which is about 6/s (Massaro, 1976). This may imply that the alternation between different counts cannot be managed by nonverbal means and indeed requires verbal, albeit covert, counting.

The fact that the subdivision-paced task was already somewhat difficult even at the slowest tempo means that our tempi did not span the whole range from possible to impossible with regard to mental subdivision, but merely the range from difficult to impossible. Although such fast tempi are perhaps rarely adopted for uneven rhythms in Western music performance, where explicit subdivisions are usually present in one form or another, we were specifically interested in how uneven rhythms would be produced when the uneven beats themselves become the lowest level in the metrical hierarchy. This situation is perhaps comparable to that in other musical traditions in which uneven beats are said to constitute elementary units (Magill & Pressing, 1987).

Rhythm Production

INTERVAL RATIOS

Previous studies (Essens & Povel, 1985; Povel, 1981; Repp et al., 2002) have shown that even musically trained individuals cannot produce the 3:2 ratio accurately, even when the tempo is slow enough for counting to be possible (i.e., slower than our slowest tempo), and that the ratio deviates in the direction of 2:1. The present study only partially confirms this finding. Seven out of 8 participants produced the set A rhythms with inflated ratios already at the slowest tempo, and 5 out of 8 produced the set B rhythms in that way. However, only 2 out of 8 participants sharpened the ratio of the set C rhythm at the outset; the majority started out with reduced ratios, suggesting assimilation of long and short intervals. Thus, the specific interval structure of rhythms seems to have an influence on the nature and degree of ratio distortion, and there are considerable individual differences as well.

[5] In Repp (2003), synchronization was considered unsuccessful when the standard deviation of the asynchronies exceeded 40% of the IOI duration. Here, a fixed 50 ms criterion was used. Both criteria easily identified trials with phase drift, and only a few ambiguous trials could have been classified differently according to the different criteria.

All three sets of rhythms ended up having sharpened interval ratios at fast tempi, when subdivision was no longer possible. The interval ratio in set A did not show a significant change with tempo (as in Repp et al., 2002), although both increases and decreases in ratio were observed at the individual level. In the three-interval rhythms of sets B and C, the ratio increased significantly with tempo. The average ratio in all rhythm sets fell short of 2, however, and it is unclear whether the rhythms produced at fast tempi should be considered instances of 2:1 rather than of 3:2. After all, they were intended to be productions of 3:2, and they might still be perceived as instances of 3:2, at least if a possible perceptual bias in favor of 2:1 is minimized. Although 2:1 ratios are sometimes softened in the context of realistic music performance (Gabrielsson et al., 1983), they are produced rather accurately in simpler rhythmic contexts (Povel, 1981; Repp et al., 2002). It seems likely, therefore, that rhythms with intended 2:1 interval ratios would be distinguishable from those produced in the present study, even at fast tempi.

Repp et al. (2002) found a reduction of the 3:2 ratio in three-interval rhythms as tempo increased, whereas we found here the opposite. This difference must be due to the fact that the rhythms of Repp et al. contained a very short interval that contrasted with the two longer intervals, whereas the present rhythms contained only two nominal interval durations that contrasted with each other. In each case, maintenance of contrast was important, but with three nominal interval durations only one contrast could be maintained at fast tempi, which happened to be the one between the short and the two longer intervals.

There is not much to be gained from maintaining simple ratios at tempi that prevent metrical subdivision. When uneven beats constitute the lowest level in a metrical hierarchy, the only real simplification would be to make them even, but this is contrary to the intention to produce uneven beats. The particular interval ratios produced at fast tempi may be a consequence of the kinematics of the rhythmic gestures and/or of perceptual distortions (i.e., assimilation) in interval perception. Our findings may provide an interesting parallel to certain fast African rhythms that are based on non-isochronous subdivisions (Magill & Pressing, 1987) and at the same time exhibit complex interval ratios (Arnould Massart, personal communication). Our participants may have been forced into a mode of operation that resembled more the action-driven rhythms of West Africa than the rational hierarchical schemes of Western musical thinking.

Remarkably, production of interval ratios was no more accurate in synchronization with a precise rhythm template than in self-paced or downbeat-paced rhythm production. Evidently, the error feedback received from the tap-tone asynchronies did nothing to enhance rhythmic accuracy; it merely served to maintain approximate average synchrony (i.e., across all taps) from cycle to cycle. Conversely, rhythm production did not disintegrate when synchronization was impossible in the subdivision-paced condition of Session III. On the contrary, interval ratios were most accurate in that condition. This admittedly may reflect an effect of practice, but the point here is that the inability to synchronize in no way diminished the accuracy of rhythm production. The factors that influence interval ratios thus seem to be independent of the processes engaged by synchronization. This seems more consistent with a kinematic than with a perceptual explanation of sharpened interval ratios.

Interval ratios (but not their variability) decreased across the three sessions. Because the three continuation tasks were different, the decrease could reflect a task effect. However, the synchronization tasks of Sessions I and II were identical, and there was no Condition × Session interaction in the ANOVA on Sessions I and II. This suggests an effect of practice. It would be worth investigating whether uneven rhythms can be produced accurately after extended practice, or by members of a culture whose music frequently employs uneven rhythms or meters (cf. Hannon & Trehub, 2005).

One entirely expected effect was that interval variability depended on interval duration. This was reflected both in greater variability of long than short intervals and in a decrease in variability as the tempo increased.[6] These differences were smaller than Weber's law would predict, however. If we had analyzed variability in terms of coefficients of variation, the effects of interval duration and tempo would most likely have remained significant, but they would have been reversed in direction. We did not conduct these analyses because Weber's law was not one of the topics that concerned us in this study. Likewise, we did not attempt an analysis of interval covariance structure (cf. Magill & Pressing, 1987), although this remains a possible project for the future.

[6]Evidently, no lower limit of movement speed was reached at fast tempi, because that should have caused an increase in variability and a decrease in interval ratios, which did not occur. The shortest produced intervals (about 200 ms) were still longer than the shortest intervals that can be produced in continuous isochronous tapping (e.g., Todor & Kyprie, 1980; Truman & Hammond, 1990).

TEMPORAL GROUPING AND METRICAL INTERPRETATION

We predicted differences in relative difficulty between the rhythms in each set, according to whether the metrical downbeat did or did not coincide with a grouping accent. The set A rhythms consist of a repeating temporal group of two tones or taps, and because the final element in such a group tends to be perceived as accented (Povel & Okkerman, 1981), we expected 3+2 (where the downbeat is group-final) to be easier to produce than 2+3 (where the downbeat is group-initial). Indeed, we observed slightly smaller interval variability in 3+2 than in 2+3, especially during continuation tapping. However, 3+2 was somewhat more difficult to synchronize with a rapid pulse train (Session III) than was 2+3. The set B rhythms consist of a repeating group of three tones or taps in which the first and third elements tend to be perceived as accented (Povel & Essens, 1985), so we predicted that 2+3+2 (where the downbeat is group-medial) would be more difficult than 2+2+3 and 3+2+2. Indeed, several participants had difficulties producing 2+3+2 at very fast tempi. The 2+3+2 rhythm was also more difficult to synchronize with a rapid pulse train than the other two rhythms in the set, exhibited greater variability of asynchronies in synchronization with a rhythm template, and showed a different patterning of asynchronies from the other set B rhythms. In set C, although the temporal grouping was more ambiguous than in the other two sets, we expected that 3+2+3 (where we assumed the downbeat to be group-medial) would be more difficult to produce than 2+3+3 and 3+3+2. Indeed, 3+2+3 was most difficult to synchronize with rapid subdivisions and also showed greater interval variability at slow tempi. Unexpectedly, however, the variability of downbeat asynchronies in downbeat-paced tapping was highest in 2+3+3. Thus, our expectations concerning the relative difficulty of the various rhythms were only partially confirmed.

Perhaps the most important finding of this study is that metrical interpretation had little effect on interval ratios and their variability. On the whole, the produced intervals were similar for all rhythms in each set; that is, they did not depend on the location of the metrical downbeat. Metrical interpretation was reflected, however, in a tendency to produce downbeat taps with greater force. Although these metrical effects were small compared to the effects of group position on tapping force, they nevertheless provide evidence that participants did not simply ignore the instructions and give all rhythms within a set the same metrical interpretation. Other recent studies (Repp, 2005; Repp & Saltzman, 2002) have likewise found effects of metrical interpretation on rhythmic performance to be elusive. Downbeat placement seems to be largely a cognitive, internal act that leaves few traces in overt behavior, at least when it is in competition with temporal grouping accents.[7]

Effects of group position on tapping force were probably less a reflection of grouping accent as such than of the duration of the interval preceding a tap: The shorter that interval is, the less time there is for an upward excursion of the finger (cf. Repp & Saltzman, 2002). For the same reason, the force of all taps, but especially of the weaker taps, decreased substantially as the tempo increased, to the extent that some taps were not even registered. Although fatigue in the course of a block of trials may also have played a role, reduced movement amplitude is likely to have been the major factor (cf. Kay, Kelso, Saltzman, & Schöner, 1987). Fatigue may likewise have something to do with the lower tapping force during self-paced continuation than during synchronization, although there is again an alternative explanation: Self-paced tapping may be a more relaxed activity than synchronization with a rhythm template.

A final comment is in order about cognitive grouping, as distinct from temporal grouping. Temporal grouping is a physical stimulus property that strongly biases the cognitive grouping of events, especially when no other grouping cues (such as pitch contour or articulation) are available. Nevertheless, even when temporal grouping is the only stimulus property relevant to grouping, listeners might be able to regroup events at a cognitive level, if that was their intention. This is most obviously the case with the rhythms in set C, whose temporal grouping is ambiguous, but even the rhythms in set A and B could in theory be conceived in terms of groupings other than those suggested by their temporal structure. However, such cognitive (re)grouping requires mental effort and hence a motive. The only motivating force in our study was metrical interpretation. Thus, it is possible that participants cognitively regrouped the events to be more consistent with a particular metrical interpretation. For example, the 2+3+2 rhythm, rather than being construed "naturally" as a temporal group with a group-medial metrical accent (i.e., as upbeat–downbeat–afterbeat), might have been thought of as a downbeat-initiated group whose boundaries coincide with the metrical framework (i.e., as downbeat–afterbeat$_1$—afterbeat$_2$). However, because metrical interpretation was the only possible motivation for potential cognitive regrouping, we did not find it necessary to consider cognitive grouping as a separate factor in our study. Whatever effects cognitive regrouping may

[7]Clear effects of metrical interpretation on synchronization accuracy have been obtained in recent experiments that varied downbeat location in isochronous melodies (Repp, in preparation).

have had on rhythm production and synchronization were confounded with effects of metrical interpretation, which were modest enough. We also suspect that grouping accents (Povel & Okkerman, 1981; Povel & Essens, 1985) depend solely on temporal grouping and cannot be altered by cognitive regrouping. Therefore, we doubt that cognitive regrouping, if it occurred, facilitated rhythm production. A proper study of cognitive grouping as an independent phenomenon requires performance on a musical instrument, so that intended groupings can be conveyed by means of articulation and phrasing.

Synchronization

The mean asynchronies during synchronization with a rhythm template reflected the sharpened interval ratios and therefore varied with temporal group position. The group-initial tap lagged behind its pacing tone or (in set C) was more or less on time, whereas the group-medial and group-final taps preceded their respective pacing tones. Synchronization was quite accurate on a cycle-by-cycle basis, with only a slight anticipation tendency (negative asynchrony) overall that tended to disappear as the tempo increased. In other words, participants timed their taps so as to minimize the mean asynchrony per cycle. It is noteworthy that the mean standard deviation of asynchronies was smaller than would be expected in synchronization with an isochronous sequence having the same cycle duration (i.e., smaller than about 3% of the mean cycle duration; cf. Figure 4).[8] This suggests that all asynchronies contributed to phase error correction and that the mean IOI duration rather than cycle duration determined variability.

One hypothesis that was not confirmed is that, in synchronizing with a rhythm template, downbeat taps would exhibit both smaller and less variable asynchronies than metrically weak taps. The absolute magnitude of the downbeat asynchronies was not significantly different from that of the asynchronies on weak beats, and their variability tended to be greater, suggesting that phase error correction affected downbeats more than weak beats.

That all asynchronies play a role in synchronization was also strikingly demonstrated by large differences in downbeat asynchronies between template-paced (synchronization) and downbeat-paced (continuation) tapping in Session II. Whereas group-initial downbeats tended to lag and group-final downbeats tended to lead their pacing tones in synchronization with a rhythm template, the opposite was true in synchronization with a sequence of downbeats. The differences in the former condition represent mainly an effect of temporal group position and thereby help maintain a small overall asynchrony for the rhythm cycle. In the latter condition, the overall asynchrony would seem to be identical with the downbeat asynchrony, but this would predict a constant downbeat asynchrony, regardless of group position. That group position still had an (albeit reversed) effect suggests that the other taps, even though they did not yield any asynchronies, nevertheless somehow affected the determination of subjective synchrony. Wohlschläger and Koch (2000) have demonstrated that taps interpolated between beats in a 1:1 synchronization task affect the mean asynchrony. The present finding suggests that the temporal placement (and resulting grouping) of the intervening taps also plays a role. Moreover, the downbeat asynchronies were much more variable during downbeat-paced tapping than during synchronization with a rhythm template. Clearly, the presence of tones on weak beats aided synchronization, and this implies that error correction occurred in response to asynchronies on all beats, not just on downbeats.

Conclusions

Our study has shown that uneven rhythms can be produced at tempi that prevent subdivision into elementary metrical units, albeit with distorted interval ratios that increase as a function of tempo. The contrast between long and short intervals was enhanced but did not approach a simple 2:1 ratio. Remarkably, these distortions occurred even when the taps were synchronized with a precise rhythmic template. Effects of metrical interpretation on rhythm production and synchronization were small compared to effects of temporal grouping.

Acknowledgments

This research was supported by NIH grant MH-51230. During preparation of the manuscript, the first author also received support from NIH grants DC-03663 and HD-01994. We are grateful to Anders Friberg, Stephen Handel, Erin Hannon, and an anonymous reviewer for helpful comments. Peter Keller is now at the Max Planck Institute for Cognitive and Brain Sciences, Leipzig, Germany.

Address correspondence to: Bruno Repp, Haskins Laboratories, 300 George Street, New Haven, CT, 06511-6624. E-MAIL *repp@haskins.yale.edu*

[8]Cycle durations ranged from 850 to 500 ms in set A, from 1190 to 700 ms in set B, and from 1360 to 800 ms in set C.

References

ASCHERSLEBEN, G. (2002). Temporal control of movements in sensorimotor synchronization. *Brain and Cognition, 48*, 66-79.

DRAKE, C., & PALMER, C. (1993). Accent structures in music performance. *Music Perception, 10*, 343-378.

ESSENS, P. J., & POVEL, D.-J. (1985). Metrical and nonmetrical representations of temporal patterns. *Perception & Psychophysics, 37*, 1-7.

FRAISSE, P. (1956). *Les structures rythmiques* [Rhythmic structures]. Louvain, Belgium: Publications Universitaires.

FRIBERG, A., & SUNDSTRÖM, A. (2002). Swing ratios and ensemble timing in jazz performance: Evidence for a common rhythmic pattern. *Music Perception, 19*, 333-350.

GABRIELSSON, A., BENGTSSON, I., & GABRIELSSON, B. (1983). Performance of musical rhythm in 3/4 and 6/8 meter. *Scandinavian Journal of Psychology, 24*, 193-213.

HANNON, E. E., & TREHUB, S. E. (2005). Metrical categories in infancy and adulthood. *Psychological Science, 16*, 48-55.

KAY, B. A., KELSO, J. A. S., SALTZMAN, E. L., & SCHÖNER, G. (1987). Space-time behavior of single and bimanual rhythmic movements: Data and limit cycle model. *Journal of Experimental Psychology: Human Perception and Performance, 13*, 178-192.

LERDAHL, F., & JACKENDOFF, R. (1983). *A generative theory of tonal music*. Cambridge, MA: MIT Press.

LONDON, J. (1995). Some examples of complex meters and their implications for models of metric perception. *Music Perception, 13*, 59-77.

LONDON, J. (2002). Cognitive constraints on metric systems: Some observations and hypotheses. *Music Perception, 19*, 529-550.

LONDON, J. (2004). *Hearing in time*. New York: Oxford University Press.

MAGILL, J. M., & PRESSING, J. L. (1997). Asymmetric cognitive clock structures in West African rhythms. *Music Perception, 15*, 189-221.

MASSARO, D. W. (1976). Perceiving and counting sounds. *Journal of Experimental Psychology: Human Perception and Performance, 2*, 337-346.

PETERS, M. (1989). The relationship between variability of intertap intervals and interval duration. *Psychological Research, 51*, 38-42.

POVEL, D.-J. (1981). Internal representation of simple temporal patterns. *Journal of Experimental Psychology: Human Perception and Performance, 7*, 3-18.

POVEL, D.-J., & ESSENS, P. (1985). Perception of temporal patterns. *Music Perception, 2*, 411-440.

POVEL, D.-J., & OKKERMAN, H. (1981). Accents in equitone sequences. *Perception & Psychophysics, 30*, 565-572.

REPP, B. H. (1997). Variability of timing in expressive piano performance increases with interval duration. *Psychonomic Bulletin & Review, 4*, 530-534.

REPP, B. H. (1999). Relationships between performance timing, perception of timing perturbations, and perceptual-motor synchronization in two Chopin preludes. *Australian Journal of Psychology, 51*, 188-203.

REPP, B. H. (2003). Rate limits in sensorimotor synchronization with auditory and visual sequences: The synchronization threshold and the benefits and costs of interval subdivision. *Journal of Motor Behavior, 35*, 355-370.

REPP, B. H. (2005). Rate limits of on-beat and off-beat tapping with simple auditory rhythms: 2. The roles of different kinds of accent. *Music Perception, 23*, 000-000.

REPP, B. H., & SALTZMAN, E. L. (2002). *Influences of grouping and metrical structure on the kinematics of rhythmic finger tapping*. Unpublished manuscript (http://www.haskins.yale.edu/haskins/STAFF/repp.html).

REPP, B. H., WINDSOR, L., & DESAIN, P. (2002). Effects of tempo on the timing of simple musical rhythms. *Music Perception, 19*, 565-593.

SEMJEN, A., & IVRY, R. B. (2001). The coupled oscillator model of between-hand coordination in alternate-hand tapping: A reappraisal. *Journal of Experimental Psychology: Human Perception and Performance, 27*, 251-265.

STERNBERG, S., KNOLL, R. L., & ZUKOFSKY, P. (1982). Timing by skilled musicians. In D. Deutsch (Ed.), *Psychology of music* (pp. 182-240). Orlando, FL: Academic.

SUMMERS, J. J., BELL, R., & BURNS, B. D. (1989). Perceptual and motor factors in the imitation of simple temporal patterns. *Psychological Research, 50*, 23-27.

TODOR, J. I., & KYPRIE, P. M. (1980). Hand differences in the rate and variability of rapid tapping. *Journal of Motor Behavior, 12*, 57-62.

TRUMAN, G., & HAMMOND, G. R. (1990). Temporal regularity of tapping by the left and right hands in timed and untimed finger tapping. *Journal of Motor Behavior, 22*, 521-535.

VORBERG, D., & WING, A. (1996). Modeling variability and dependence in timing. In H. Heuer & S. W. Keele (Eds.), *Handbook of perception and action, vol. 2* (pp. 181-262). London: Academic Press.

WEISBERG, A. (1993). *Performing twentieth-century music: A handbook for conductors and instrumentalists*. New Haven, CT: Yale University Press.

WOHLSCHLÄGER, A., & KOCH, R. (2000). Synchronization error: An error in time perception. In P. Desain & L. Windsor (Eds.), *Rhythm perception and production* (pp. 115-127). Lisse, The Netherlands: Swets & Zeitlinger.