

Perception–production relationships and phase correction in synchronization with two-interval rhythms

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Abstract Two experiments investigated the effects of interval duration ratio on perception of local timing perturbations, accuracy of rhythm production, and phase correction in musicians listening to or tapping in synchrony with cyclically repeated auditory two-interval rhythms. Ratios ranged from simple (1:2) to complex (7:11, 5:13), and from small ($5:13 = 0.38$) to large ($6:7 = 0.86$). Rhythm production and perception exhibited similar ratio-dependent biases: rhythms with small ratios were produced with increased ratios, and timing perturbations in these rhythms tended to be harder to detect when they locally increased the ratio than when they reduced it. The opposite held for rhythms with large ratios. This demonstrates a close relation between rhythm perception and production. Unexpectedly, however, the neutral “attractor” was not the simplest ratio ($1:2 = 0.50$) but a complex ratio near 4:7 ($= 0.57$). Phase correction in response to perturbations was generally rapid and did not show the ratio-dependent biases observed in rhythm perception and production. Thus, phase correction operates efficiently and autonomously even in synchronization with rhythms exhibiting complex interval ratios.

Rhythmic regularity and sensorimotor synchronization

The ability to synchronize rhythmic movements to an external rhythm in the environment—whether it is produced by conspecifics, other species, or mechanical sources—may be unique to humans amongst primates (Brown, 2007; Kirschner & Tomasello, 2009; Merker, Madison, & Eckerdal, 2009). Moreover, some human activities, most notably music and dance, make special use of our general capacity for rhythmic production and synchronization, as the temporal synchronies involved in these arts are essential both amongst the performers and between performer(s) and audience. Our delight in a dancer’s steps or a pianist’s solo depends in large part on our ability to follow along and “inwardly second” the kinematic or musical activity (Levinson, 1997), even if the observed movement and sound sequences are complex and not necessarily within our own individual behavioral repertoire (Schubotz, 2007). This reflects the tight coupling between perceptual and motor processes in the human action system (see, e.g., Hommel, Müssele, Aschersleben, & Prinz, 2001).

Technically any series of sounds or events that has duration can be called a “rhythm”; the greater the number of component durations and variety of their sequential organization, the more complex the rhythm (London, 2001). However, to call a series of sounds or motor behaviors “rhythmic” generally connotes a sense that there is a small number of elements that occur in a repeating or a quasi-repeating pattern, and that those elements occur in a temporal range that lies comfortably within the limits of human temporal perception and motor action (i.e., between 100 ms and 2–3 s; see London, 2004). The simplest patterns involve the repetition of a single interval; these “stationary” or “isochronous” rhythms have been the subject of good deal of psychophysical and sensorimotor

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research, dating back to the nineteenth century (see Repp, 2005, for a review of recent literature). More complex rhythms involve combinations of long and short elements, taxonomies of which go back to Aristoxenus (fourth century BC; see Cooper & Meyer, 1960; for more recent attempts to quantify rhythmic complexity, see Pressing, 1999; Shmulevich & Povel, 2000; Thul & Toussaint, 2008).

The simplest non-isochronous rhythm is a repeating rhythmic pattern consisting of a short and long interval, where the intervals are marked by the onsets of short tones or drumbeats. Such a pattern can be described as (1) a longer cycle duration that is subdivided into two uneven intervals by a medial event (hierarchical interval structure), (2) a short interval followed by a long interval—or vice versa, given its cyclical nature (serial interval structure), or (3) a group of two tones or drumbeats separated by a longer interval from the next group (grouping structure). Quantitatively, such patterns can be described by the cycle duration or repetition rate and either the ratio between one interval and the cycle duration (hierarchical) or the ratio formed by the short and long intervals (serial). Hierarchical ratios are often used in music, but serial ratios are more commonly used in psychological studies of rhythm, and we follow that usage, always placing the smaller interval first (except in the first four figures).¹ If expressed as fractions, interval ratios thus assume values between 0 and 1.

Production and perception of two-interval rhythms

It is commonly presumed that isochronous rhythms are the easiest to produce and thus also afford the easiest and most tightly coordinated sensorimotor synchronization. Among two-interval rhythms, those whose short and long intervals have simple integer ratios (e.g., 1:2 or 1:3) are also considered to be easy to produce and readily afford synchronization. Such rhythms are common in music notation, and the presence of a simple integer unit of duration in the

interval ratio (the “1” of the 1:2 or 1:3 ratio) reflects an implicit isochronous substrate that is manifest in the shorter interval. Rhythms without such a surface manifestation, even if they have relatively simple interval ratios (e.g., 2:3) seem more difficult to render accurately (Repp, London, & Keller, 2005; Snyder, Hannon, Large, & Christiansen, 2006). Yet the advantage of simple over complex ratios may not be absolute because deviations from simple ratios are common in musical contexts, where such deviations give expressive character to a rhythm (see, e.g., Friberg & Sundström, 2002; Gabrielsson, Bengtsson, & Gabrielsson, 1983; Honing & de Haas, 2008).

The ability to perceive and reproduce two-interval rhythms varying in interval ratio has been assessed in a number of studies (Collier & Wright, 1995; Fraise, 1946; Povel, 1981; Semjen & Ivry, 2001; Sternberg, Knoll, & Zukofsky, 1982; Summers, Bell, & Burns, 1989; Summers, Hawkins, & Mayers, 1986). It is commonly observed that most target interval ratios are systematically distorted in reproduction. For example, Povel (1981) presented cyclic rhythms instantiating eight different interval ratios ranging from 1:4 (0.25) to 4:5 (0.80), holding either the cycle duration or the short interval constant. The 1:2 ratio (0.50) was reproduced most accurately whereas all other produced ratios deviated substantially from their respective target ratios in the direction of 1:2. This means that target ratios smaller than 0.50 increased, so that their interval durations became more similar (assimilation), whereas target ratios larger than 0.50 decreased, so that their interval durations became more different (contrast). Subsequent studies have shown that these trends are independent of whether the rhythms are tapped unimanually or with alternating hands (Semjen & Ivry, 2001; Summers et al., 1989), and musical training was found to have no effect (Summers et al., 1986, 1989). In one study (Repp et al., 2005), musicians produced 2:3 rhythms in synchrony with an exact auditory pacing sequence; even so, systematic deviations from the target ratio were observed, similar to those found in a self-paced condition. Collier and Wright (1995) showed that deviations from specified ratios persist even in musicians who have practiced the rhythms with visual feedback of their performance accuracy.

Povel (1981) attributed the gravitation towards a 1:2 “attractor” (we borrow this term from the dynamic systems literature) to an internal beat-based coding of rhythmic patterns. Basically, this amounts to mentally bisecting the long interval and thereby imposing the isochronous substrate appropriate for the 1:2 rhythm on all rhythms in the set, while at the same time being aware of the difference between each target rhythm and 1:2 and thus trying to counteract the reduction of the rhythm to 1:2. Certainly, Povel’s results seemed to demonstrate that two different intervals cannot easily be produced independent of each

¹ Dynamic systems approaches to rhythmic bimanual coordination also employ a form of hierarchical interval ratio, namely relative phase (e.g., Haken, Kelso, & Bunz, 1985; Tuller & Kelso, 1989; Yamanishi, Kawato, & Suzuki, 1980). A 1:2 interval ratio implies a 1:3 ratio between the shorter interval and the cycle duration (a normalized relative phase of 0.33). It is well known that in-phase and anti-phase movements are easy to perform accurately, whereas other phase relationships between the hands are more difficult to produce, show greater variability, and are typically distorted in the direction of the closer of the two “attractors,” in-phase and anti-phase. These studies, however, are usually not concerned with the production of musical rhythm, and they often use visual pacing signals (but see Semjen & Ivry, 2001). In bimanual production of auditory two-interval rhythms, in-phase and anti-phase movements both imply isochrony and thus are avoided (i.e., do not function as attractors) unless the two target interval durations are difficult to discriminate.

other in a serial fashion, and that rhythm production has an underlying hierarchical structure (Vorberg & Hambuch, 1978, 1984). Vorberg and Wing (1996) elaborated this idea into the rhythm program hypothesis, according to which target intervals are specified by a hierarchical program but are then executed in serial fashion.

The perception of two-interval rhythms has rarely been investigated in the absence of (re)production (but see Sternberg et al., 1982). Because the rhythm to be produced is usually presented as a physical model, the error observed in reproduction may arise in perception of the model as well as in perceptual monitoring of the sensory feedback from the rhythm production itself. The finding of similar distortions of various target ratios in bimanual and unimanual rhythm production (Semjen & Ivry, 2001; Summers et al., 1989) also suggests that the distortions do not arise in the movement kinematics but in prior or posterior perceptual specifications. A Bayesian framework supporting a close relationship between rhythm perception and production has been developed by Sadakata, Desain, and Honing (2006).

In the present study, our aim was to make two contributions to this topic. First, we wanted to confirm that distortions of interval ratios in the direction of 1:2 occur even under conditions maximally conducive to accurate rhythm production, namely when the participants are highly trained musicians and the task is synchronization with the exact target rhythms. We certainly expected the ratio deviations to be smaller than in previous studies, but if a similar pattern were found, this would attest to their obligatory and deeply rooted nature. Second, we designed a purely perceptual task to test the hypothesis that a similar pattern of ratio-dependent asymmetries would be observed in two-interval rhythm perception. This task required the detection of small local deviations from the interval ratio in one or the other direction. Our hypothesis was that a deviation in the direction of the 1:2 ratio (which momentarily mimics the distortion observed in production) should be more difficult to detect than a deviation in the opposite direction. The hypothesis can be seen as being related to a more general principle: a change from a more typical to a less typical stimulus is often easier to perceive than the reverse, probably because perception or memory of the less typical stimulus is distorted towards a prototype that functions as a perceptual attractor. For example, in musical contexts it has been shown that: timing deviations are more difficult to perceive when they resemble expressive deviations in music performance than when they do not (Repp, 1998a, b); it is easier to detect a change from a metrically regular to an irregular rhythm or meter than the reverse (Bharucha & Pryor, 1986; Hannon & Trehub, 2005); mistuned pitch intervals are easier to detect when they follow rather than precede in-tune intervals (Schellenberg, 2001). In the

present context, the 1:2 ratio could be considered as the prototypical interval ratio of a two-interval rhythm.

Orthogonal to this investigation of a close parallel between rhythm perception and production, our study also addressed another issue, namely how phase correction operates in synchronization with two-interval rhythms.²

Phase correction in synchronization

Phase correction (or sensorimotor coupling, in dynamic systems terminology) is required for the maintenance of synchrony. This process has been investigated mainly with isochronous metronomes (see Repp, 2005, for a review) and occasionally with more complex metrical sequences (Large, Fink, & Kelso, 2002; Repp, London, & Keller, 2008), but not yet with sequences exhibiting arbitrarily complex interval ratios. One frequently used method is to introduce a small local timing perturbation and examine the largely automatic adjustment of the timing of the next tap, the phase correction response (PCR). As the magnitude of the PCR varies linearly with perturbation magnitude (as long as the perturbation is relatively small), it can be expressed as a percentage of the latter. The PCR is usually less than 100% but increases with interval duration in isochronous sequences (Repp, 2008a, b). It does not depend on conscious perception of the timing perturbation that elicits it, and the linearity of the PCR function (which relates PCR magnitude to perturbation magnitude and passes through the origin) suggests that psychophysical detection thresholds do not limit phase correction (Repp, 2000, 2001). Moreover, other variables that affect the detectability of a timing perturbation usually leave the PCR unaffected (Repp, 2006, 2009). These findings indicate that the PCR is not based on perception of intervals between successive sound onsets. More commonly, it is assumed that the PCR reflects perception of intervals between taps and sound onsets (i.e., asynchronies), but this hypothesis, too, is contradicted by the linearity of the PCR function. It has been argued instead that taps constitute timed reactions to sound onsets that are counteracted by a tendency to maintain a constant tapping period (Hary & Moore, 1985, 1987; Repp, 2005, 2008a, b). The maintenance tendency is assumed to decrease with tempo (i.e., with increasing period duration), and it might also be reduced when the period is not constant, as in two-interval rhythms.

² This was really the primary purpose of this research, at least as we saw it initially. However, because we obtained rhythm production data as a byproduct of the synchronization task that we employed to measure phase correction and then realized the perception task could easily be conducted with the identical materials, we did not want to miss this opportunity to compare rhythm production and perception. Thus, we expanded the scope of the present research.

In a recent study, we investigated for the first time phase correction in non-isochronous but still metrical (i.e., simple-ratio) two- and three-interval rhythms (Repp et al., 2008). The ratio between the shorter and longer intervals in these rhythms was always 2:3. (In the three-interval rhythms, one of the intervals occurred twice; i.e., 2:2:3 or 2:3:3.) Musically trained participants tapped along with the cyclically repeated rhythms, and their PCR to small local phase perturbations was measured. There were three main findings. First, the overall magnitude of the PCR was similar to that in synchronization with isochronous sequences; the fact that 2:3 is a more complex interval ratio than 1:1 did not seem to reduce the efficiency of phase correction. The finding that phase correction was not more efficient in synchronization with non-isochronous than with isochronous rhythms is problematic for the just-mentioned hypothesis of period maintenance, but it could be argued that the maintenance tendency is not restricted to isochrony and extends to repeated interval patterns. Second, in two-interval rhythms the PCR was larger when it was preceded by the longer interval (because the phase perturbation had occurred at the end of the shorter interval) than when it was preceded by the shorter interval. This result seemed consistent with the previously found increase in the PCR with interval duration in isochronous sequences (Repp, 2008a, b). Surprisingly, however, we found no effect of preceding interval duration on the PCR in three-interval rhythms. Our third finding was that the metrical interpretation of the rhythms (i.e., which tone in the rhythm cycle was conceived as representing the main beat) had no impact on the PCR.

In the present study, we wished to extend these previous findings by investigating the PCR to phase perturbations in sensorimotor synchronization with two-interval rhythms having arbitrary interval ratios that varied in complexity and magnitude. We had three main predictions. First, given our previous findings with 2:3 rhythms (Repp et al., 2008), we expected phase correction to operate efficiently regardless of ratio complexity and magnitude, much like in synchronization with isochronous sequences. Second, we expected the PCR to increase with the duration of the preceding interval, because we had found such an increase in 2:3 and isochronous rhythms. Third, given earlier findings showing independence of the PCR from conscious interval perception and judgment (Repp, 2001, 2005, 2006, 2009), we did not expect phase correction to exhibit ratio-dependent asymmetries in response to phase perturbations of different sign, unlike what we expected to find in explicit perception of these very same perturbations (as described in the preceding section).

The current study thus marries two, hitherto separate but closely related lines of research; one addressing the relationship between rhythm perception and production, and the other concerned with phase correction in sensorimotor synchronization. We report two similar experiments that

differ in the specific interval ratios used. In “[Experiment 1](#)”, cycle duration (the sum of the two intervals) remained constant across rhythms varying in interval ratio, whereas in “[Experiment 2](#)”, cycle duration varied across rhythms while one of the two intervals was held constant (cf. Povel, 1981). We did not control or manipulate metrical interpretation of the rhythms (i.e., whether the first or the second tone in the two-tone group is conceived as the stronger beat) because our previous results (Repp et al., 2008) had shown convincingly that it is irrelevant to sensorimotor synchronization and temporal rhythm production.

Experiment 1

Methods

Participants

The participants included nine highly trained musicians, all graduate students at the Yale School of Music (6 women, aged 22–28), who were paid for their services, and author BHR (aged 64). All were regular participants in perception and synchronization experiments in BHR’s lab. The musicians’ primary instruments, which they had studied intensively for many years, were piano (2), harp, violin (2), viola, double bass, clarinet, and bassoon; BHR is an amateur pianist with much experience in synchronization tasks. (Any clear differences between BHR’s results and those of the young musicians will be pointed out.)

Materials and equipment

Tone sequences were generated on-line by a program written in MAX 4.0.9, running on an Intel iMac computer. The tones (piano timbre) were produced by a Roland RD-250s digital piano according to musical-instrument-digital-interface (MIDI) instructions from the MAX program and were presented over Sennheiser HD540 reference II headphones. All tones had the same pitch (D#4, 311 Hz), the same nominal duration (40 ms, with rapid decay after the nominal offset), and the same intensity (MIDI velocity). Participants tapped on a Roland SPD-6 electronic percussion pad. Finger impacts were audible as thus whose loudness depended on individual tapping force.

Each rhythmic sequence consisted of a cyclically repeated pair of tones that, together with the next tone, defined two inter-onset intervals (IOIs) whose sum was 1,080 ms (the cycle duration). The duration of the first IOI ranged from 300 to 780 ms in increments of 60 ms, which resulted in nine interval conditions: 300/780, 360/720, 420/660, 480/600, 540/540, 600/480, 660/420, 720/360, and 780/300 ms. Given the cyclical presentation of these conditions,

listeners heard a repeating group of two tones separated by the shorter of the two IOIs (except in the isochronous 540/540 condition, unless subjective binary grouping occurred—see Bolton, 1894; Brochard, Abecasis, Potter, Ragot, & Drake, 2003), with the longer IOI separating the perceptual groups. Consequently, there were only five distinct rhythms because 300/780 and 780/300, for example, represent the same rhythm. When we refer to a rhythm, we mean the two conditions with the same IOIs, regardless of order. The ratios formed by the two IOIs in the five rhythms are 5:13, 1:2, 7:11, 4:5, and 1:1, which correspond to fractions of 0.38, 0.50, 0.64, 0.80, and 1.00.

Each sequence contained ten local phase shifts whose magnitude ranged from -50 to 50 ms in increments of 10 ms (not including zero). A phase shift amounts to a change in a single IOI, which was always the first IOI in the cycle of an interval condition. Consequently, the tap exhibiting the PCR always occurred at the end of the cycle. The difference between two interval conditions of the same rhythm (e.g., 300/780 and 780/300) lay in whether the short (within-group) or long (between-group) interval was perturbed. This is illustrated schematically in Fig. 1. The order in which the ten phase shift magnitudes were applied in a sequence varied randomly. The first phase shift occurred in the sixth, seventh, eighth, or ninth cycle. The number of unperturbed cycles following a perturbed cycle varied randomly from 2 to 5. The number of cycles in each sequence thus varied within a possible range of 36 to 69.

Procedure

Participants came for two 1-h sessions that were typically 1 week apart. The first session was always the synchronization task; the second session was the perception task.

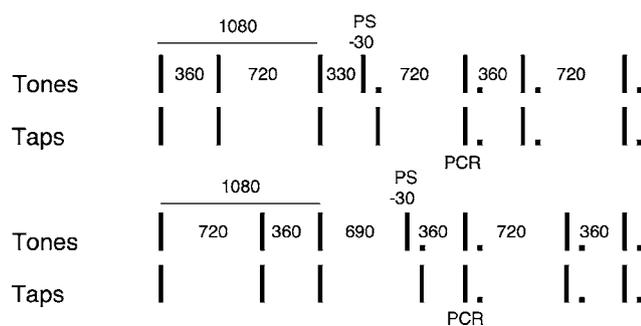


Fig. 1 Schematic illustration of -30 ms phase shifts (*PS*) in interval conditions 360/720 (*above*) and 720/360 (*below*). Three cycles are shown; *numbers* indicate interval durations (ms). *Vertical bars* indicate tones or taps; *dots* indicate where these events would have occurred in the absence of a *PS*. The *PS* shortens the first interval of the second cycle by 30 ms. This results in an increase of the local tone–tap asynchrony by 30 ms. The next tap exhibits the phase correction response (*PCR*), which in this cartoon (but not typically) compensates completely for the *PS*. Thus, the *PCR* is -30 ms

In the synchronization task, participants held the percussion pad on their lap and tapped with the index or middle finger of their right hand. (All participants were right-handed.) They started each sequence by pressing the space bar of the computer keyboard and started tapping as soon as they felt ready. The task was to make a tap with each tone and synchronize taps and tones as closely as possible. Participants were told that most rhythms were not strictly metrical and that small local deviations from the main rhythm might occur. Five blocks of nine sequences each (representing the nine interval conditions) were presented, with short breaks between blocks. The order of sequences was freshly randomized in each block.

In the perception task, participants listened to five blocks of the same nine interval conditions and tried to detect the phase shifts. They were instructed to keep the index finger of their right hand on the down-arrow key of the computer keyboard and press the key as quickly as possible whenever they heard a deviation from the rhythm that was established at the beginning of the sequence.

Results

In the following, we describe results pertaining to (1) the accuracy of rhythm production in the synchronization task, (2) the detection of phase shifted tones in the perception task, and (3) the operation of phase correction in the synchronization task.

Synchronization task: rhythm production

Figure 2 shows the rhythm production results in terms of the mean asynchronies of taps with the two tones (first, second) delimiting the first IOI in the two-interval cycle, because in this format the results can be compared directly with the results of the perception task. Asynchronies of taps

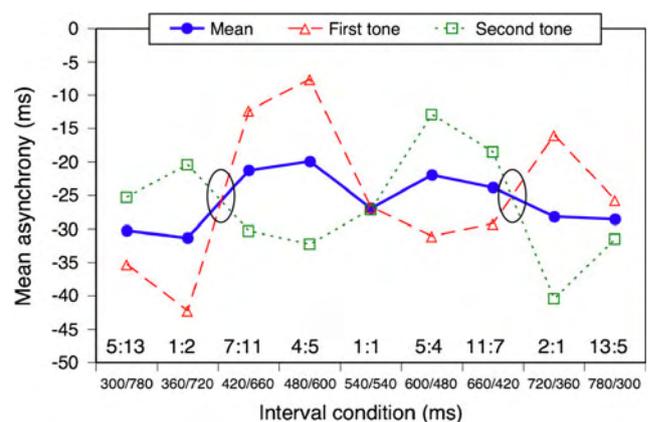


Fig. 2 Experiment 1: mean asynchronies for the nine interval conditions, and separately for first and second tones in the cycle. *Ovals* denote attractor points

with phase-shifted (second) tones and PCR-taps with the following (first) tones (see Fig. 1) were included; their positive and negative deviations were expected to cancel in the means. Figure 2 reveals that mean asynchronies were negative, implying that the taps preceded the tones, as is commonly found in synchronization with isochronous sequences. There were but slight differences in mean asynchrony among the five rhythms. However, the non-isochronous rhythms exhibited differences in asynchronies with first and second tones in cycles, and these asymmetries went in opposite directions for the 5:13 and 1:2 rhythms on the one hand and the 7:11 and 4:5 rhythms on the other. A more negative asynchrony with the first than with the second tone when the first IOI is short (300/780, 360/720) and the opposite when the first IOI is long (720/360, 780/300) implies assimilation of IOI durations and an increase in the short–long ratio above the target ratio. A less negative asynchrony with the first than with the second tone when the first IOI is short (420/660, 480/600) and the opposite when the first IOI is long (600/480, 660/420) implies increased contrast of IOI durations and a decrease in the short–long ratio below the baseline ratio. Thus, as predicted, the 5:13 (0.38) rhythm showed assimilation, which moved it closer to 1:2 (0.50), whereas the 7:11 (0.64) and 4:5 (0.80) rhythms showed increased contrast, which likewise moved them closer to 1:2, the hypothetical attractor ratio. Unexpectedly, however, the 1:2 rhythm showed assimilation as well and thus did not seem to represent a neutral attractor. The attractor suggested by the data is indicated by the cross-overs highlighted by ovals in Fig. 2; it lies between the 1:2 (0.50) and 7:11 (0.64) rhythms. (For a plot of the actual produced ratios, which are not of primary interest here, see Fig. 1D in Repp, London, and Keller, 2010, a follow-up study that focuses on ratio production.)

To assess the reliability of these observations, a $2 \times 4 \times 2$ repeated-measures ANOVA was conducted, without the 540/540 condition, with the variables defined as follows: position of short IOI (first or second in cycle), short IOI duration (increasing from 300 to 480 ms), and tone position (terminating the short vs. the long IOI). This way of looking at the data amounts to interchanging the triangles and squares in the right half of Fig. 2 (conversion to tone position) and folding the right onto the left half by rotating it around a vertical axis (mapping of short IOIs onto each other). There was a significant main effect of short IOI duration, $F(3, 27) = 10.85$, $p = 0.001$, reflecting the somewhat smaller negative mean asynchronies in the 7:11 and 4:5 rhythms than in the 5:13 and 1:2 rhythms.³ Also significant was the interaction between tone position and short IOI duration, $F(3, 27) = 29.86$, $p < 0.001$, which

indicates that different rhythms exhibited different asymmetries. When the asymmetry was tested in separate 2×2 ANOVAs on each rhythm, the main effect of tone position was found to be significant in all cases: 5:13, $F(1, 9) = 8.09$, $p = 0.019$; 1:2, $F(1, 9) = 74.09$, $p < 0.001$; 7:11, $F(1, 9) = 13.15$, $p = 0.006$; 4:5, $F(1, 9) = 10.18$, $p = 0.011$. It is noteworthy that the unexpected asymmetry in 1:2 was the most consistent by far.

Figure 3 shows the standard deviations of the asynchronies, which are of interest as well. As expected, the isochronous 1:1 rhythm was produced with lower variability than the non-isochronous rhythms. However, the variability of the simple ratio 1:2 rhythm was no different from that of the complex ratio 5:13 rhythm. Variability was generally inflated by the inclusion of asynchronies associated with phase shifts and PCRs, but more so for second tones (coinciding with phase shifts) than for first tones (coinciding with PCRs) because PCRs were generally smaller than phase shifts (see below). The magnitude of this artifactual difference could be gauged in the isochronous 1:1 rhythm, where phase shifts and PCRs were the only plausible causes of a difference in variability between “second” and “first” tones. Therefore, the variability functions for first and second tones shown in Fig. 3 are shifted vertically, so as to nullify their difference in the 1:1 rhythm, as indicated by the arrows. This adjustment makes it easier to see that variability of asynchronies depended on the duration of the preceding IOI (i.e., the second IOI in the preceding cycle for the first tone, and the first IOI in the current cycle for the second tone), being larger for long than for short IOIs. This effect can be seen as a reflection of the general principle that temporal uncertainty in interval production and perception increases with interval duration (e.g., Peters, 1989). We will refer to this relation henceforth as the temporal uncertainty principle, without making

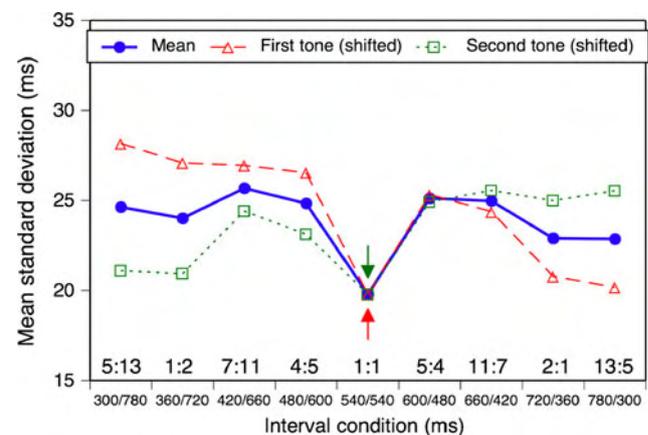


Fig. 3 Experiment 1: mean standard deviations of asynchronies for the nine interval conditions, and separately for first and second tones in the cycle. (Functions shifted towards each other, as indicated by arrows.)

³ The Greenhouse–Geisser correction was applied to the p value of any effect with more than two levels.

any claims that the data conform to any particular formal model such as scalar timing or Weber's law (e.g., Gibbon, 1977).

An ANOVA on the variability data, with the same variables as in the analysis of asynchronies, revealed a significant main effect of short IOI duration, $F(3, 27) = 16.61$, $p < 0.001$, due to smaller variability of asynchronies in the 5:13 and 1:2 rhythms than in the 7:11 and 4:5 rhythms. The interaction between tone position and short IOI duration was also significant, $F(3, 27) = 8.92$, $p = 0.008$, because only the variability of asynchronies of taps with the tone terminating the short IOI increased with short IOI duration (squares on the left, triangles on the right in Fig. 3), in accord with the temporal uncertainty principle. Obviously, the variability of asynchronies of taps with the tone terminating the long IOI did not increase with the duration of the short IOI, but it increased barely with the duration of the long IOI (triangles on the left, squares on the right), which was unexpected in view of the temporal uncertainty principle.

Perception task

To assess the detection of phase shifted tones in the different rhythms, we accepted responses as hits if they occurred within 200–1,200 ms after the end of a changed IOI. The modal response time was near 400 ms. The mean number of rejected responses (very late responses and false alarms) per sequence was 0.79.

The hit percentages for the nine interval conditions, averaged across all phase shift magnitudes and also averaged separately across negative and positive phase shifts, are shown in Fig. 4. Clearly, detection scores decreased as the duration of the changed IOI (the first IOI in the cycle)

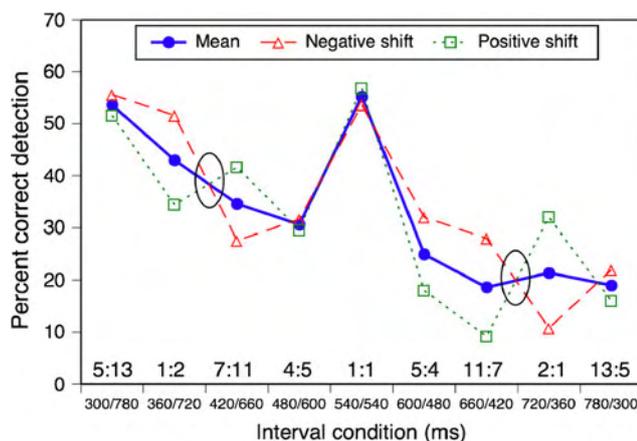


Fig. 4 Experiment 1: mean percent correct detection scores in the nine interval conditions, and separately for negative and positive phase shifts. Ovals denote attractor points

increased, in accord with the temporal uncertainty principle in perception, although the decrease was steepest at the shortest durations and did not extend beyond 660 ms, which matches the just-noted lack of an effect of long IOI duration on asynchrony variability (Fig. 3). The isochronous condition was an exception, as predicted: here detection scores were much higher than expected on the basis of IOI duration alone and equaled those for the shortest IOI duration (300 ms) in non-isochronous rhythms. However, with the gradient due to the temporal uncertainty principle taken into account, there was no indication of better performance in the 1:2 (= 2:1) rhythm than in adjacent rhythms with more complex interval ratios. Furthermore, Fig. 4 shows asymmetries in the detection of negative and positive phase shifts (IOI shortenings and lengthenings, respectively), and these asymmetries differed among rhythms. Unexpectedly, but consistent with the rhythm production data (Fig. 2), the 1:2 rhythm exhibited a strong asymmetry: a lengthening of the shorter IOI (a positive shift in 360/720) and a shortening of the longer IOI (a negative shift in 720/360), both of which increased the ratio between the short and long IOIs, were more difficult to detect than the opposite changes. The 7:11 rhythm showed exactly the opposite pattern; here, as predicted, changes that decreased the ratio between the short and long IOIs (i.e., in the direction of 1:2), were harder to detect than the opposite changes. The ovals in Fig. 4 indicate the hypothetical attractor ratio that does not show any asymmetry, which is located again between 1:2 and 7:11.⁴

A $2 \times 4 \times 2$ repeated-measures ANOVA was conducted on these data, with the 540/540 condition excluded. The variables were short versus long first IOI (i.e., the left versus right halves of Fig. 4), first IOI duration (four levels, increasing), and phase shift direction (negative, positive). The difference in detection scores between short and long IOIs was extremely robust, $F(1, 9) = 194.31$, $p < 0.001$. IOI duration within these two ranges also had a clear effect, $F(3, 27) = 28.00$, $p < 0.001$, but the interaction was significant, $F(3, 27) = 7.29$, $p = 0.002$, because the decrease in detection scores with increasing IOI duration was greater for short than for long IOIs. Finally, the interaction between IOI duration and phase shift direction was significant, $F(3, 27) = 21.28$, $p < 0.001$, which reflects varying asymmetries in the detectability of negative and positive phase shifts across the rhythms. Separate 2×2

⁴ These results would change little if the perception data were analyzed in terms of fitting psychometric functions to the response percentages and comparing their slopes and 50% thresholds. It was clear from inspection of the average response functions that, whenever a change was more difficult to detect, the function had both a shallower slope and a higher threshold, and in some cases it did not reach 50%.

ANOVAs on each individual non-isochronous rhythm revealed these asymmetries—reflected here in an interaction between interval condition ($m:n$ vs. $n:m$) and phase shift direction—to be significant for the 1:2 rhythm, $F(1, 9) = 31.85$, $p < 0.001$, and for the 7:11 rhythm, $F(1, 9) = 19.30$, $p = 0.002$, but not for the 5:13 or 4:5 rhythms. However, the 4:5 rhythm showed a significant main effect of phase shift direction, $F(1, 9) = 7.42$, $p = 0.023$, as well as a tendency toward an interaction, $F(1, 9) = 3.43$, $p = 0.097$, due to the presence of an asymmetry in 600/480 but not in 480/600 (see Fig. 4).

Synchronization task: phase correction response

The PCR to a phase shift was calculated by subtracting the tap-tone asynchrony at the time of the phase shift from the subsequent asynchrony (see Fig. 1). The statistical expectation of this difference is zero in the absence of phase correction, and it is equal to the phase shift if phase correction is immediate and perfect. The PCRs for the same perturbation magnitude were averaged across the five repetitions (trial blocks) before regressing them onto perturbation magnitude (10 data points). The slope of the regression line, multiplied by 100, expresses the mean PCR as a percentage of perturbation magnitude.⁵ Thus, a PCR of 100% means phase correction was perfect with the very next tap, while a PCR of 0 means there was no immediate phase correction at all.

Figure 5 shows the mean PCR as a function of interval condition. As predicted, the PCR tended to get smaller as the preceding IOI (the second IOI in the cycle) got shorter. (Note that the preceding inter-tap interval, which may be the real cause of the effect, resembled the preceding IOI.) One-way repeated-measures ANOVA showed the differences among interval conditions to be significant, $F(8, 72) = 5.76$, $p = 0.001$, due to a significant linear trend, $F(1, 9) = 15.65$, $p = 0.003$. However, this trend was entirely due to a decrease across the long IOIs (780–600 ms, left half of Fig. 5), where the PCR occurred in the first tap of a group of two. When the PCR occurred in the second tap of a group, which followed a short IOI, the PCR actually tended to increase as the preceding IOI decreased from 480 to 300 ms (right half of Fig. 5). This was quite unexpected.

Taking the just-mentioned trends into account, there was no indication that phase correction was any more effective in the 1:2 rhythm than in rhythms with more complex interval ratios. The same could be said for the isochronous

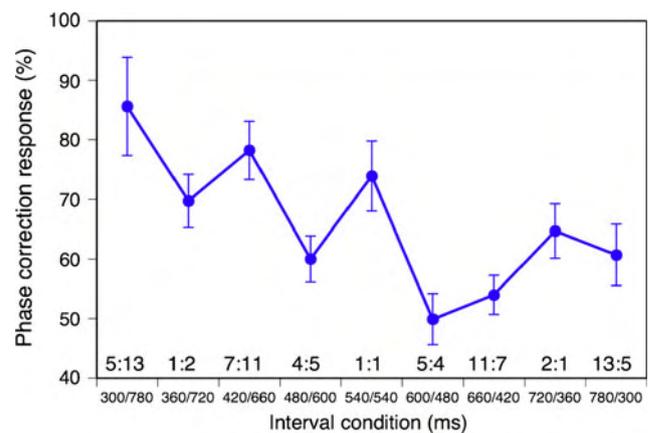


Fig. 5 Experiment 1: mean phase correction response as a percentage of perturbation magnitude in the nine interval conditions. Error bars represent ± 1 standard error

1:1 rhythm, except that its mean PCR seemed distinctly larger than that of the adjacent 4:5 (= 5:4) rhythm, a difference that was significant when tested separately, $F(2, 18) = 6.39$, $p = 0.024$. This difference became even larger and more reliable, $F(2, 16) = 13.93$, $p = 0.002$, when author BHR's data were omitted, for BHR was unique in showing a smaller mean PCR with the 1:1 rhythm than with any other rhythm, which may have been due to his long experience with isochronous tapping tasks (see Repp, 2010a).

We further investigated whether there were any significant asymmetries in PCRs to negative and positive phase shifts, similar to those observed in perception (Fig. 4) and production (Fig. 2). We did this by fitting second-order polynomial curves to the individual PCR functions and examining the quadratic coefficients.⁶ Given the strong linear increase of the PCR with perturbation magnitude, convexity (a negative quadratic coefficient) indicates a stronger PCR to negative than to positive phase shifts, whereas concavity (a positive coefficient) indicates the opposite. One-way repeated-measures ANOVA on the quadratic coefficients fell short of significance, $F(8, 72) = 2.13$, $p = 0.089$. However, there was a significant linear trend, $F(1, 9) = 16.11$, $p = 0.003$, indicating increasingly positive coefficients as the IOI preceding the PCR decreased. This trend does not resemble the pattern of asymmetries observed in rhythm perception and production. There were also large individual differences in PCR asymmetry.

⁵ Each PCR function also yielded a measure of the y-axis intercept. This intercept was different from zero in non-isochronous rhythms and corresponded closely to the difference between the mean asynchronies of taps with first and second tones (Fig. 2).

⁶ We first attempted to derive separate PCR estimates for negative and positive phase shifts by regression analysis, but the results were highly variable due to the small number of data points. Therefore, separate PCRs for negative and positive phase shifts are not shown in Fig. 5.

Discussion

Experiment 1 tested several predictions with regard to rhythm production, rhythm perception, and phase correction. Considering rhythm production first, our prediction based on earlier findings in the literature was that the 5:13 (0.38) rhythm, whose interval ratio is smaller than 1:2 (0.50), would be produced with a larger interval ratio (assimilation), whereas the two rhythms with ratios larger than 1:2, namely 7:11 (0.64) and 4:5 (0.80), would be produced with smaller ratios (contrast). Both predictions were confirmed, even though the participants were highly trained musicians who tapped in synchrony with an exact auditory template. Although these ratio distortions were smaller than those observed in earlier studies of rhythm reproduction with less highly trained participants (Povel, 1981; Summers et al., 1986, 1989), they seemed to be difficult to avoid completely.

We also expected that the 1:2 rhythm would be produced most accurately, as in the earlier studies just cited. Surprisingly, however, it was produced with a significantly increased ratio, indicating interval assimilation. There was also no indication of lower variability of the 1:2 rhythm compared to its more complex neighbors. These results indicate that, in this experiment at least, the simple 1:2 ratio was not inherently more stable than other non-isochronous rhythms, nor did it seem to function as an attractor. The attractor ratio, the one for which there is neither assimilation nor contrast, was situated between 1:2 and 7:11. It is possible that the attractor ratio is not necessarily a simple ratio, and that it depends on the range of ratios used in an experiment (however, see Repp et al., 2010). Also, even though the present participants were musicians, they may not have interpreted 1:2 as a familiar instance of triple meter because it occurred in the context of various complex-ratio rhythms.

With regard to perception of non-isochronous rhythms, we predicted asymmetries that mirror the asymmetries in production: in a rhythm whose production shows interval assimilation (an increase in interval ratio), a perturbation that momentarily increases the interval ratio should be harder to detect than a perturbation that decreases the interval ratio, and the opposite for rhythms whose production shows the contrast. This prediction was confirmed for the 1:2 and 7:11 rhythms. The 4:5 rhythm showed a non-significant tendency in the predicted direction. Only the 5:13 rhythm differed, in that it showed no asymmetry in perception. The reason for this is not clear. Like the rhythm production data, the rhythm perception data suggest a complex attractor ratio located between 1:2 and 7:11. Overall, the results suggest a close relation between rhythm perception and production, consistent with other

studies in the literature (Repp, 1998a, b; Sadakata et al., 2006).

As predicted, the isochronous rhythm was produced with lower variability of asynchronies than non-isochronous rhythms. (This would undoubtedly also be true for interval variability, which we did not analyze here; see Doumas & Wing, 2007.) The 1:1 rhythm also enabled better detection of timing deviations (cf. Yee, Holleran, & Jones, 1994). A change in the 540 ms interval in the isochronous sequence was as easy to detect as the same absolute change in a 300 ms interval in a non-isochronous sequence. This shows that the internal representation of any two-interval combination is less stable than that of a single interval.

Some findings reflect the well-known relationship between interval duration and temporal uncertainty. Variability of taps at the end of an interval increased with interval duration, although only between 300 and 600 ms. In perception, detectability of a change clearly decreased as interval duration increased, but also mainly across shorter intervals. This may be due to a floor effect at long intervals, where the phase shifts were very difficult to detect. However, it is also possible that participants were engaged in mental subdivision of long intervals, thereby attenuating the effect of interval duration.

Several predictions were tested with regard to the PCR. First, we predicted that it would not vary greatly among different rhythms, including the isochronous one. There was indeed not much difference between the 5:13, 1:2, 7:11, and 1:1 rhythms, but phase correction was less effective in the 4:5 rhythm than in the isochronous rhythm, at least for the young musician participants. This may have been due to the near-isochrony of the 4:5 rhythm. It was not the case, however, that phase shifts that increased this ratio (i.e., made it locally more isochronous) were more difficult to adjust to than phase shifts in the opposite direction. A second prediction was that the PCR should increase with the duration of the preceding IOI. The data offered some support for this hypothesis, but only when the IOI was the longer of the two in the cycle (i.e., when it was the between-group IOI). This makes sense in terms of a parallel with isochronous tapping, where grouping is weak or absent. However, the absent or even inverted effect of within-group IOI duration on the PCR remains puzzling because it seems that strong group coherence (a short IOI) should reduce within-group flexibility in tap timing and thus yield a small PCR. A third prediction was that, unlike rhythm perception and production, the PCR would not exhibit any asymmetries in response to negative and positive phase shifts. Although an asymmetry in favor of positive phase shifts emerged as the IOI preceding the

PCR decreased, this trend did not resemble the asymmetries observed in rhythm perception and production.⁷

Experiment 2

While the perception and production results of Experiment 1 were very clear and largely consistent with each other, the PCR results exhibited considerable variability, and the predicted dependence of the PCR on preceding interval duration was only partially obtained. Although there is much evidence from previous research that the PCR is independent of perception of timing perturbations (Repp, 2000, 2001, 2005), a skeptic could argue that any increase of the PCR with preceding IOI duration (the second IOI in the cycle) could have been due to increasing detectability of the phase shift (the change in the first IOI) because the first IOI decreased as the second IOI increased. In Experiment 2, we used a new set of rhythms whose cycle duration was allowed to vary (cf. Povel, 1981). Varying one IOI while holding the other IOI constant allowed us to dissociate effects of the two IOI durations.

The PCR was expected to increase with the duration of the second IOI (that preceded it) but to be unaffected by the duration of the first IOI. Detection scores in the perception task, in contrast, were expected to decrease with the duration of the first IOI (that was changed by a phase shift) but to be unaffected by the duration of the second IOI. Ratio-dependent asymmetries in rhythm production and perception were again expected to be present and show close parallels, as in Experiment 1, whereas the PCR was not expected to exhibit such asymmetries.

Methods

Several months had elapsed since Experiment 1. The participants were the same as previously, but one (a violinist) was not able to do the perception task because of scheduling problems. Equipment, basic construction of materials, design, and procedure were also the same.

In the new set of seven non-isochronous interval conditions, the first IOI in a cycle was always shorter than the second IOI (which made each interval condition a unique

⁷ We note here briefly that Experiment 1 was preceded by a very similar experiment in which the timing perturbations were event onset shifts (Repp, 2002) rather than phase shifts. Event onset shifts change both IOIs in a cycle in a complementary fashion, thereby creating a larger change in interval ratio than a phase shift created in the present experiment. However, the results were almost identical and therefore are not reported here in detail. In the perception task, participants generally responded to the change in the shorter IOI, but the pattern of asymmetries was the same as in Fig. 4. The analysis of PCRs yielded only one reliable effect, a larger PCR in the 1:1 than in the 4:5 rhythm (cf. Fig. 5).

rhythm), and only the first IOI could be changed by a phase shift. The tap exhibiting the PCR thus always followed the long (between-group) IOI and thus coincided (approximately) with the first tone in a cycle. Only one rhythm, 360/720 (1:2) was shared with Experiment 1. Two 1:1 rhythms, one fast (360/360) and the other slow (840/840), were included for comparison; they were expected to demonstrate the increase in the PCR with interval duration observed previously in isochronous sequences (Repp, 2008a, b). Within one subset of the rhythms, the second IOI increased while the first IOI was held constant: 360/360 (1:1), 360/480 (3:4), 360/600 (3:5), 360/720 (1:2), 360/840 (3:7). The opposite was the case within the other subset, which shared the 360/840 rhythm: 360/840 (3:7), 480/840 (4:7), 600/840 (5:7), 720/840 (6:7), 840/840 (1:1). Across all these rhythms, cycle duration increased linearly from 720 to 1,680 ms in increments of 120 ms.

Results

The results for rhythm production, phase shift detection, and phase correction during sensorimotor synchronization are reported below in similar fashion to the results of Experiment 1.

Synchronization task: rhythm production

The mean asynchronies are shown in Fig. 6. There was a significant main effect of rhythm, $F(8, 72) = 12.63$, $p < 0.001$. Although it is common to find smaller negative asynchronies in synchronization with fast than with slow isochronous rhythms (Mates, Radil, Müller, & Pöppel, 1994; Repp, 2003), the difference between 360/360 and 840/840 was surprisingly small here and barely significant, $F(1, 9) = 5.77$, $p = 0.040$. The main effect was primarily due to differences among the non-isochronous rhythms in

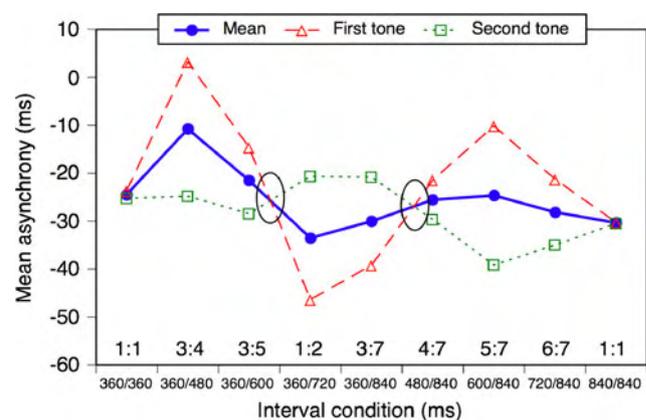


Fig. 6 Experiment 2: mean asynchronies for the nine interval conditions, and separately for first and second tones in the cycle. Ovals denote attractor points

which the second, longer IOI increased (3:4 to 3:7), $F(3, 27) = 27.31, p < 0.001$. There were no reliable differences in mean asynchrony among the non-isochronous rhythms in which the first, shorter IOI increased (3:7 to 6:7), $F(3, 27) = 1.41, p = 0.265$.

Of primary interest are the predicted asymmetries, which were clearly present, as evidenced by a significant interaction between rhythm and tone position (first versus second in cycle), $F(8, 72) = 7.82, p = 0.004$. It is also evident that they were mainly due to differences in asynchronies with first (group-initial) tones, $F(8, 72) = 15.57, p < 0.001$, whereas differences in asynchronies with second (group-final) tones were smaller, though also significant when tested separately, $F(8, 72) = 5.12, p = 0.007$. Assimilation of interval durations was shown by two rhythms, 1:2, $t(9) = -6.54, p < 0.001$, and 3:7, $t(9) = -3.39, p = 0.008$, whereas increased contrast of interval durations was evident in 3:4, $t(9) = 5.05, p = 0.001$, 3:5, $t(9) = 5.07, p = 0.001$, 5:7, $t(9) = 3.43, p = 0.007$, and 6:7, $t(9) = 0.92, p = 0.381$. The last effect was not significant because three participants showed the opposite tendency (assimilation), one of them in quite extreme form, suggesting that she tapped almost isochronously. Thus, the 6:7 rhythm was close enough to isochrony to fall within the narrow range of the 1:1 attractor for some participants. The 4:7 rhythm showed no significant asymmetry, as it was close to the second crossover of the dashed and dotted functions in Fig. 6. The two crossovers of the functions (ovals in Fig. 6) are roughly consistent with each other and suggest an attractor ratio close to 4:7, consistent with Experiment 1.

The variability of asynchronies is portrayed in Fig. 7. The mean standard deviation differed significantly among rhythms, $F(8, 72) = 27.29, p < 0.001$. As expected, isochronous rhythms showed lower variability than

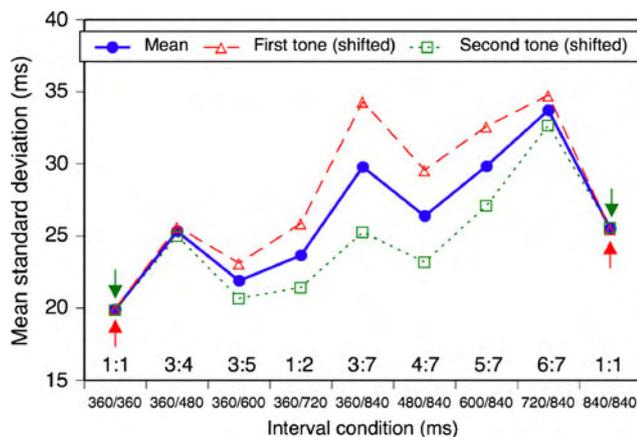


Fig. 7 Experiment 2: mean standard deviations of asynchronies for the nine interval conditions, and separately for first and second tones in the cycle. (Functions shifted towards each other, as indicated by arrows.)

adjacent non-isochronous rhythms: 360/360 versus 360/480, $F(1, 9) = 17.71, p = 0.002$; 720/840 versus 840/840, $F(1, 9) = 29.85, p < 0.001$. Also as expected, variability in tapping with 840/840 was greater than in tapping with 360/360, $F(1, 9) = 32.13, p < 0.001$, due to the temporal uncertainty principle. The variation among non-isochronous rhythms was more complex. Variability tended to increase with cycle duration (i.e., from left to right in Fig. 7), which was fully expected, but there were local peaks for 3:4 and 3:7. Perhaps a better interpretation would be that the data show reduced variability for 3:5, 1:2, and 4:7, which are all in the vicinity of the attractor ratio.

As in Fig. 3, a correction for artifactually larger variability of second-tone than first-tone asynchronies, due to phase shifts versus PCRs, was implemented by shifting the dashed and dotted functions in Fig. 7 so as to nullify their difference in the isochronous rhythms, as indicated by the arrows. (The difference was almost exactly the same in 360/360 and 840/840.) The interaction between rhythm and tone position was highly reliable, $F(8, 72) = 11.75, p < 0.001$. It can be seen that asynchrony variability was greater for first tones (which followed the second, longer IOI) than for second tones (which followed the first, shorter IOI), consistent with the temporal uncertainty principle. Moreover, this difference increased as the longer IOI increased (3:4 to 3:7) because this increased the variability of first-tone asynchronies more than that of second-tone asynchronies, and the difference decreased as the shorter IOI increased (3:7 to 6:7) because this increased the variability of second-tone asynchronies more than that of first-tone asynchronies.

Perception task

The same cutoff for hits (i.e., accurate detection of phase shifted tones) was used as in Experiment 1, and the distribution of response times was similar. The mean false alarm rate was 0.91 per sequence.

The results are shown in Fig. 8. There were significant differences in detection scores among the rhythms, $F(8, 64) = 58.74, p < 0.001$. The mean detection scores show the expected pattern: first, detection in isochronous rhythms was considerably better than in the adjacent non-isochronous rhythms: $F(1, 8) = 29.83, p = 0.001$, for 360/360 versus 360/480, and $F(1, 8) = 78.13, p < 0.001$, for 720/840 versus 840/840. Second, detection was much better in 360/360 than in 840/840, $F(1, 8) = 99.34, p < 0.001$, which reflects the temporal uncertainty principle. Third, detection scores in non-isochronous rhythms decreased as the duration of the first IOI (the IOI changed by the phase shift) increased from 360 ms (3:7) to 720 ms (6:7), $F(3, 24) = 79.01, p < 0.001$, again in accord with the temporal uncertainty principle. Finally, as predicted,

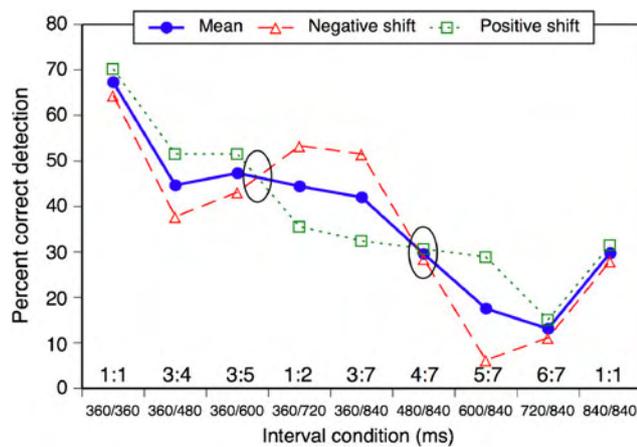


Fig. 8 Experiment 2: mean percent correct detection scores in the nine interval conditions, and separately for negative and positive phase shifts. Ovals denote attractor points

detection scores in non-isochronous rhythms did not change significantly as the duration of the second (unchanged) IOI increased from 480 ms (3:4) to 840 ms (3:7), $F(3, 24) = 2.01$, $p = 0.157$.

The predicted asymmetries with regard to perception of negative and positive phase shifts were also present. Overall, there was a significant interaction between rhythm and phase shift direction, $F(8, 64) = 6.61$, $p = 0.002$, which confirms the presence of different asymmetries for different rhythms. As in Experiment 1, the 1:2 rhythm was not neutral but favored detection of negative shifts, which decreased the interval ratio, over positive shifts, which increased the ratio, $t(8) = 2.66$, $p = 0.033$. The same asymmetry was shown by the only rhythm with a ratio smaller than 1:2, namely 3:7, $t(8) = 3.71$, $p = 0.006$. In contrast, three of the rhythms with ratios larger than 1:2 showed the reverse asymmetry: 5:7, $t(8) = -4.15$, $p = 0.003$; 3:4, $t(8) = -2.76$, $p = 0.025$; and 3:5, $t(8) = -2.67$, $p = 0.028$. Two rhythms showed no asymmetry: 4:7, which lies at the second cross-over of the dashed and dotted functions in Fig. 8 and thus emerges as a potential attractor ratio, and 6:7, the largest ratio, which is close to isochrony. The first cross-over of the dashed and dotted functions in Fig. 8 occurs at a ratio of about 3:5.3, which is very nearly the same ratio as 4:7 (a fraction of 0.57). Thus, the two attractor estimates are in close agreement, and also consistent with the rhythm production data.

Synchronization task: phase correction response

Finally, we consider the variation in PCRs across rhythms, which is shown in Fig. 9. These results offer a few surprises. First, it should be noted that the mean PCRs were considerably larger than those in Experiment 1, with phase

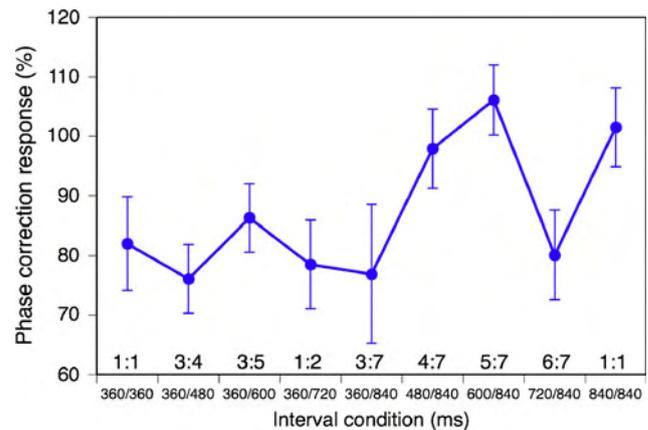


Fig. 9 Experiment 2: mean phase correction response as a percentage of perturbation magnitude in the nine interval conditions, and separately for negative and positive phase shifts. Error bars represent ± 1 standard error

correction in three rhythms (480/840, 600/840, 840/840) being instantaneous on average (mean PCR $\sim 100\%$). This rapid phase correction may be due to the fact that all perturbations occurred predictably in the shorter, within-group IOI in this experiment, so that participants could always respond by adjusting the longer, between-group inter-tap interval. Individual differences in the pattern of mean PCRs were large, but the main effect of rhythm was nevertheless significant, $F(8, 72) = 3.41$, $p = 0.019$. As predicted, the mean PCR was larger in 840/840 than in 360/360, $t(9) = 2.28$, $p = 0.048$. Both of these PCRs were considerably larger than those in previous experiments with isochronous sequences, involving some of the same participants (Repp, 2008b).⁸ This could well be due to increased flexibility (a weakening of the “maintenance tendency” hypothesized to counteract phase correction) in tapping with isochronous sequences when they occur in the context of non-isochronous rhythms.

Our most important prediction was that the mean PCR should increase with the duration of the preceding (between-group) IOI. This concerns the first five rhythms in Fig. 9 (360/360 to 360/840), but it can be seen that the mean PCR changed little within this range, $F(4, 36) = 0.38$, $p = 0.734$. Thus, our hypothesis is not at all supported by the data. On the contrary, significant variation in mean PCR occurred within the subset of rhythms in which the duration of the perturbed within-group IOI increased (360/840 to 840/840), $F(4, 36) = 4.18$, $p = 0.031$. That variation was distinctly nonlinear, however, as indicated by a highly significant cubic component

⁸ It did not seem necessary to consider the results with author BHR’s data excluded because of his small PCRs in isochronous rhythms. His mean PCR was rather small in 360/360 but comparable to that of some other participants in 840/840.

of the effect within that range, $F(1, 9) = 44.03, p < 0.001$. Clearly, this variation had nothing to do with perception of the phase shift because detection scores decreased monotonically as the within-group IOI increased, except for an increase with 840/840 (Fig. 8). Thus, these data enable us to reject once again the hypothesis that the PCR depends on perception of interval changes. However, they pose a new puzzle: Why was phase correction quicker in the 4:7 and 5:7 rhythms than in the 3:7 rhythm? We have no answer to this question at the moment. The smaller PCR in the 6:7 rhythm could be due to the closeness of this rhythm to isochrony (cf. the reduced PCR in the 4:5 rhythm in Experiment 1).

An ANOVA on quadratic coefficients of PCR functions revealed a significant difference among rhythms, $F(8, 72) = 3.41, p = 0.015$. As in Experiment 1, coefficients became increasingly positive (indicating larger PCRs to positive than to negative phase shifts) as the longer (between-group) IOI decreased. Three rhythms showed significant coefficients ($p < 0.05$) when tested individually with t tests: 1:1 (360/360), 3:4 (positive), and 5:7 (negative). However, individual differences in asymmetries were huge, and the pattern of mean asymmetries showed no resemblance to the patterns in rhythm production and perception.

Discussion

Using a different set of rhythms, Experiment 2 confirmed the close relation between distortion of interval ratios in rhythm production and perception of timing deviations. Again, the 1:2 rhythm did not serve as a neutral attractor but rather showed interval assimilation in production and a corresponding perceptual asymmetry. The real attractor seemed to be located at a slightly larger ratio, close to 4:7 (0.57).

The main reason for conducting Experiment 2 was to untangle two hypotheses with regard to the PCR that were confounded in Experiment 1: does the PCR depend on the duration of the preceding IOI or on detection of the phase shift? The results suggest that it depends on neither. Although there is much previous evidence suggesting that phase correction is independent of conscious interval perception, the lack of any effect of preceding interval duration is unexpected, although there is the precedent of Repp et al. (2008) not finding any such effect in three-interval rhythms. The PCR increases with interval duration in isochronous sequences (Repp, 2008a, b), as can be seen here in the larger PCR for 840/840 than for 360/360, and it also has been found to be larger in 2:3 rhythms when it follows the longer interval than when it follows the shorter interval (Repp et al., 2008). In Experiment 1, too, the PCR was larger when it followed the longer interval in a rhythm

than when it followed the shorter interval, and it decreased with the duration of the longer interval. In Experiment 2, it always followed the longer interval, but the effect of longer interval duration was no longer present. Instead, rhythms in which the shorter interval was lengthened exhibited enhanced phase correction. The reasons for this remain unclear.

General discussion

The present research makes several contributions to our understanding of rhythm production, rhythm perception, and phase correction in synchronization. By considering all three processes and their relationships, the experiments have furnished new data demonstrating an intimate relationship between rhythm perception and production with regard to effects of interval ratio, while also reaffirming that phase correction is largely independent of interval-based processes, even though it is essential for sensorimotor coordination.

Although the interval ratios employed in our experiments may seem unmusical (except for 1:2), it should be noted that they could well occur in musical and non-musical contexts with some frequency. In performance, musicians routinely deviate from the simple rhythmic proportions given by the notation in order to perform a rhythm with the appropriate nuance for a given genre or style (from the “swing ratio” in jazz to double dotting in French Baroque dances). Likewise, in other forms of sensorimotor coordination (dancing, game playing, sport), we entrain to uneven rhythms, as strides, arm swings, and other movements are not perfectly isochronous. Thus, these ratios are not unusual, and may be representative of what we do in both musical and non-musical rhythmic behaviors.

Although interval ratio distortions in rhythm production have been found previously, we have shown that they occur to some extent (and very reliably) even when highly trained musicians tap in synchrony with exact rhythm templates. Some degree of distortion thus seems to be unavoidable. The present perceptual task was novel and was shown to exhibit asymmetries congruent with those in rhythm production: ratio changes in the direction of the distortion observed in production were more difficult to detect than changes in the opposite direction. These results are consistent with previous findings showing that a timing deviation in a musical performance is more difficult to perceive when it makes the timing pattern more characteristic of the way in which it is typically produced (cf. Repp, 1998a, b). The distortions in rhythm production may themselves be perceptual in origin (Semjen & Ivry, 2001), reflecting gravitation toward a perceptual attractor ratio that functions as a prototype.

Unexpectedly, the present results suggest that the attractor ratio is not necessarily simple. Actually, this conclusion could already have been drawn from the results of Povel (1981) and Summers et al. (1986, 1989), for although the 1:2 ratio was produced more accurately than other ratios in these studies, it tended to show interval contrast, suggesting an attractor ratio smaller than 1:2 (0.50). In contrast, the present results indicate interval assimilation in the 1:2 rhythms and suggest an attractor ratio in the vicinity of 4:7 (0.57). We will refrain from attempting to interpret this result because of two significant limitations of our experimental design. First, we employed only one instance of a 1:2 rhythm, namely 360/720, although it occurred in the context of two different rhythm sets, one having a constant cycle duration (Experiment 1), the other a variable one (Experiment 2). Future studies need to investigate the generality of our findings for 1:2 rhythms with different cycle durations. Second, the ranges of ratios employed in the present experiments were not symmetric around 1:2 (0.50): Ratios in Experiment 1 ranged from 5:13 (0.38) to 1:1 (1.00), with a mean fraction of 0.63, whereas those in Experiment 2 ranged from 3:7 (0.43) to 1:1 (1.00), with a mean fraction of 0.71. It is quite common to find range effects in psychophysics, where perceptual judgments tend to drift towards the mean of the range (e.g., Jones & McAuley, 2005; Parducci, 1974). Also, the range of ratios in the studies of Povel (1981) and Summers et al. (1986, 1989) was more nearly symmetric or even perfectly symmetric around 0.50, though not asymmetric in the other direction. It certainly could be argued that in the present experiments the attractor was pulled away from 1:2 in the direction of the mean interval ratio. Furthermore, it could be suggested that the presence of timing perturbations in the rhythms, the requirement of synchronization, and/or the absence of explicit auditory feedback from taps (as used in the studies of Povel and Summers et al.) contributed to distortions in rhythm production. In a forthcoming study that focuses on interval ratio production (Repp et al., 2010), we address all these concerns and show them to be largely unfounded. Although some of these variables had minor effects, the “detuning” of the 1:2 attractor ratio seems to be a robust phenomenon, though we currently cannot explain it.

The present study is the first to investigate synchronization with arbitrarily complex two-interval rhythms, a task that could be carried out quite easily by our musically trained participants, albeit not with perfect accuracy. The PCR results demonstrate that phase correction in response to timing perturbations in such rhythms is by no means inferior, and sometimes even superior, to phase correction in synchronization with isochronous sequences. In other words, as long as approximate synchrony can be achieved and maintained, phase correction works rapidly and

efficiently, naturally also in the absence of perturbations (or else synchrony would be lost). Even though binary grouping of tones occurred more or less strongly in all non-isochronous rhythms, strong PCRs occurred with both group-initial and group-final perturbations. Within-group phase correction (investigated in Experiment 1 only) tended to be less efficient than between-group phase correction, but the difference was not very consistent, and within-group phase correction was remarkably good even within a 300 ms interval. The temporal limit for phase correction in response to perturbation remains to be determined; it could turn out to be as low as the “synchronization threshold” for isochronous sequences (i.e., about 120 ms; Repp, 2003). This issue is addressed in another recent study (Repp, 2010b).

To conclude, the current study has extended work on links between perception and action by examining the interplay of sensory and motor processes in the context of auditory rhythm patterns of varying complexity. The finding that rhythm perception and production exhibit similar interval ratio distortions suggests the operation of a common process that is constrained by relative interval durations. In contrast, the finding that phase correction operates to a large degree independently of rhythmic complexity and conscious perturbation detection suggests that the process of coupling one’s movements to an external auditory sequence is not subject to such constraints even when interval ratios are complex. Taken together, the results of the present study thus highlight a distinction between the perception and production of rhythmic sequences, on one hand, and the synchronization of perceived and produced sequences, on the other hand, in terms of the type of temporal information that is used to guide behavior. Although much previous research has focused either on rhythm perception and production or on basic sensorimotor synchronization, the relationships between the processes that underlie these behaviors deserve further investigation.

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