Distortions in Reproduction of Two-Interval Rhythms: When the "Attractor Ratio" Is Not Exactly 1:2

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When rhythms consisting of two unequal intervals are reproduced cyclically, their interval ratio tends to be distorted in the direction of 1:2 (= 0.5), which thus seems to function as an "attractor ratio" (AR). However, recent results for musicians in a synchronization task (Repp, London, & Keller, 2011) have suggested an upward-shifted AR (USAR) somewhat greater than 0.5. Three new experiments suggest that this shift is not due to synchronization versus continuation tapping, the range of interval ratios employed, unimanual versus bimanual tapping, intensity differences between taps, or mental subdivision of the long interval, although some of these factors may affect its size. The new results also show that the USAR is found more consistently in musicians than in nonmusicians and seems to arise in rhythm production, not in perception. While the exact causes of the USAR remain unclear, the results suggest that the AR is not necessarily the mathematically simplest interval ratio.

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The simplest non-isochronous rhythms consist of events defining two different intervals (i1 < i2) whose relationship can be described by their ratio (i1:i2) or fraction (i1/i2).[1] These rhythms basically constitute a repeated group of two events, with i1 and i2 being the within-group and between-group interval, respectively. Production or reproduction of such rhythms has been investigated in a number of studies (Fraisse, 1946, 1956; Povel, 1981; Semjen & Ivry, 2001; Sternberg, Knoll, & Zukofsky, 1982; Summers, Bell, & Burns, 1989; Summers, Hawkins, & Mayers, 1986). The theoretical question of interest is whether the intended ratio of the two interval durations, which can be varied arbitrarily in an experimental setting, exerts any constraints on the accuracy and variability of production.

Among the many possible interval ratios, the 1:2 ratio occupies a special place by virtue of its mathematical simplicity. It is a common nominal ratio between two adjacent unequal note values in music (e.g., an eighth note and a quarter note), even though in performance the ratio may deviate from 1:2 according to expressive requirements (see, e.g., Gabrielsson, Bengtsson, & Gabrielsson, 1983). Models of rhythm production postulate either nested interval hierarchies (Pressing, 1998; Vorberg & Hambuch, 1984) or coupled nonlinear oscillators (Large, 2008; Tomic & Janata, 2008) to generate two or more unequal intervals. In each type of model, the 1:2 ratio is special because it has an underlying isochrony: A single interval timer or oscillator can generate a 1:2 rhythm by rendering every third event covert. This fact suggests that the 1:2 rhythm should be produced more easily and accurately than any other two-interval rhythm.

Indeed, several experimental studies have suggested that the 1:2 ratio occupies a special place in two-interval rhythm production. In his classic studies of rhythm formation, Fraisse (1946, 1956) asked participants to improvise rhythmic patterns containing unequal intervals and found that, on average, they tapped intervals having a ratio close to 1:2, although there was considerable variability. In a more detailed investigation, Povel (1981) presented cyclically repeated two-interval rhythms with different interval ratios and required participants to first tap along and then continue tapping the rhythm for a number of cycles. The reproduction of the different interval ratios followed a characteristic pattern, which is shown graphically here in Figure 1A. The presented (target) ratios and produced ratios are

[1]Alternatively, the ratio may be defined as i1:(i1 + i2) and the fraction as i1/(i1 + i2). We prefer to use i1:i2 ratios or i1/i2 fractions because this is common practice in the literature on rhythm production.

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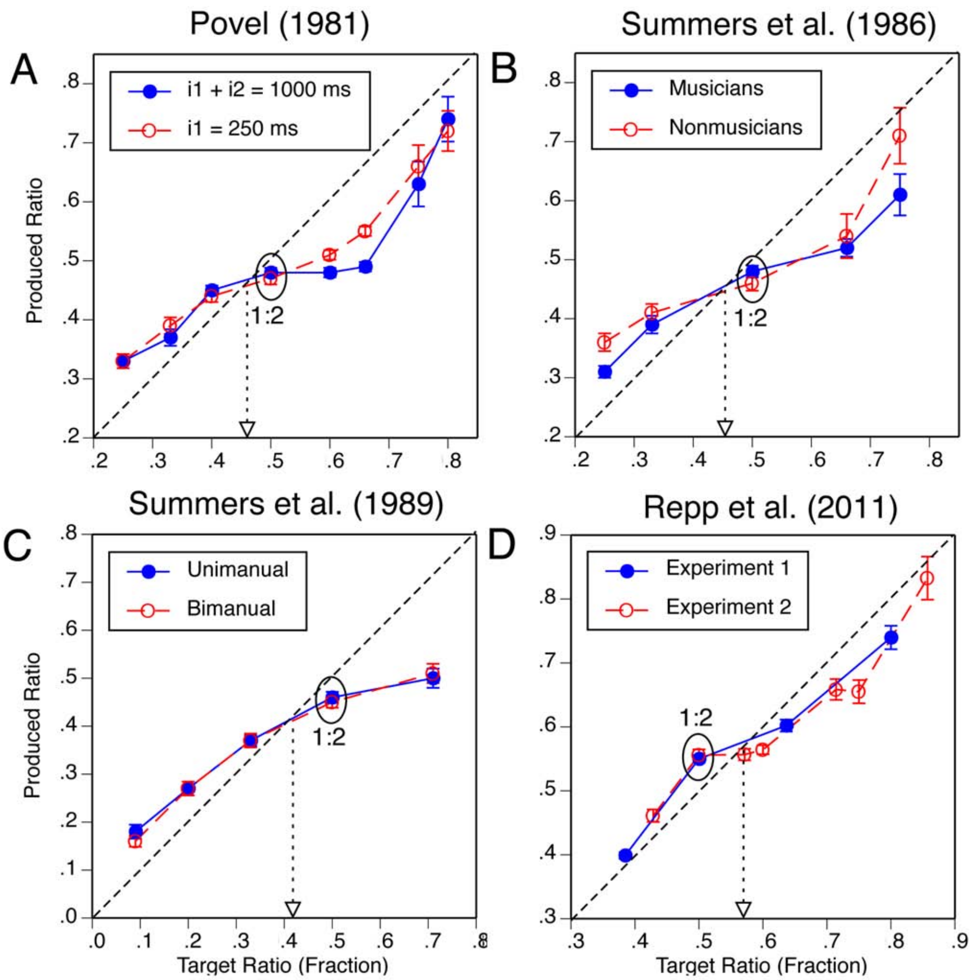

FIGURE 1. Two-interval rhythm production data from four studies: (A) Data from Table 2 in Povel (1981). The same ratios were presented either with a fixed cycle duration (i1 + i2) of 1000 ms or with a fixed short interval (i1) duration of 250 ms. (B) Data from Table 2 in Summers et al. (1986) for musicians and nonmusicians. (C) Data from Table 1 in Summers et al. (1989) for tapping unimanually with a single finger and bimanually with hands alternating. (D) Data from Repp et al. (2011) from two synchronization experiments with different selections of interval ratios. In Experiment 1, the cycle duration was fixed at 1080 ms; in Experiment 2, i1 was fixed for some rhythms, i2 for others. In each panel, data for the 1:2 ratio are highlighted (oval), the diagonal line indicates perfect performance, the vertical arrow indicates the inferred true attractor ratio, and the error bars are standard errors. Large error bars for large ratios indicate "contrary tendencies": Some participants produced these rhythms almost isochronously, which suggests that a 1:1 attractor was effective in this range.

shown as i1/i2 fractions (1:2 = 0.5), and the lines connect data points from two conditions in which the same ratios were presented either with i1 = 250 ms or with i1 + i2 = 1000 ms. In each case, the 1:2 ratio was produced most accurately, whereas production of other ratios deviated considerably from their respective target ratios. (The dashed diagonal line represents perfect performance.) Ratios smaller than 1:2 were reproduced as larger ratios, which implies reduced contrast between i1 and i2, whereas ratios larger than 1:2 were reproduced as smaller ratios, which implies increased contrast between i1 and i2. Both lines connecting data points have a shallower slope in the vicinity of 1:2, which indicates a tendency to reproduce different ratios in the same way, namely with an interval ratio close to 1:2 (i.e., a categorical tendency). This pattern of results indicates that the 1:2 ratio functions as an "attractor ratio" (AR) in the rhythm space. The AR is the ratio that would be produced without any systematic distortion, and the point at which each line crosses the diagonal gives an estimate of the AR. Because the estimates were similar in the two conditions, they are indicated by a single dotted vertical arrow in Figure 1A. The arrow points to a fraction just slightly below 0.5, probably not significantly different from 0.5.

Results from similar studies by Summers et al. (1986, 1989) are shown in Figures 1B and 1C. The earlier study compared groups of musicians and nonmusicians, and found little difference. The later study compared unimanual and bimanual (with hands alternating) tapping, and found no difference at all. (See also Semjen & Ivry, 2001.) The ranges of ratios were different from those used by Povel (1981), but the results were similar: Again, the 1:2 ratio was produced most accurately, and other ratios were distorted in the direction of the 1:2 ratio. The 1:2 ratio itself was decreased somewhat in reproduction (i.e., it showed increased contrast between i1 and i2), and the ARs suggested by the data (vertical arrows) were more clearly below 0.5 than in Povel's (1981) study. Summers et al. (1989) pointed out this deviation from the theoretical 0.5, but did not attempt to explain it.

A recent study of our own (Repp et al., 2011) unexpectedly yielded a deviation from the theoretical 1:2 AR in the opposite direction. Our participants were highly trained musicians, and they tapped two-interval rhythms unimanually in synchrony with exact auditory templates of these rhythms. The templates contained occasional timing perturbations (phase shifts) because in that study we were primarily interested in assessing the participants' phase correction response to these perturbations. Nevertheless, we could determine the accuracy with which the participants produced the various interval ratios while synchronizing with the templates. Our results from two experiments using different selections of interval ratios are shown in Figure 1D (drawn specially for the present article). We found systematic distortions of most ratios in the direction of 1:2, in agreement with earlier studies, despite the fact that participants were musically trained and guided by rhythm templates. The 1:2 ratio itself was also distorted, but here it showed significant reduction of the contrast between i1 and i2. Remarkably, this was the statistically most reliable distortion of any rhythm in the set, being very consistent across participants. Consequently, the inferred AR was larger than 1:2 and corresponded to a fraction of 0.57. We will call this effect henceforth the "upward shift of the attractor ratio" (USAR).

The USAR is interesting because it suggests (together with some of the earlier results) that the AR in two-interval rhythm production is not necessarily the mathematically simplest interval ratio (1:2), contrary to any theory that assumes that the 1:2 rhythm results from an underlying isochronous process. It is not difficult to explain why there might be an AR at 1:2 and a categorical tendency around it. But why should the AR deviate from 1:2, and why does it deviate in different directions in different studies? Here we consider a number of hypotheses and examine them systematically.

There are at least three noteworthy differences between our study (Repp et al., 2011) and those of Povel (1981) and Summers et al. (1986, 1989). One difference lies in the range of ratios used. A mental representation of the center of a temporal range can function as an attractor in perception (e.g., Jones & McAuley, 2005), and so it is conceivable that the mean of the ratios or fractions used in an experiment functions as an additional attractor in rhythm production.[2] Some of the earlier results are consistent with this interpretation: Our ranges of ratios (Figure 1D) had their centers above 1:2, which could have induced the USAR, and Summers et al. (1989) used a range whose center was below 1:2 and found a downward shift of the AR (Figure 1C). Other results, however, are not so easily accommodated: Povel used a range whose center was slightly above 1:2 (Figure 1A) and did not obtain any USAR, and Summers et al. (1986) used a range that was centered on 1:2 but obtained a downward shift (Figure 1B). Moreover, in our study, the center of the range was higher in Experiment 2 than in Experiment 1, but the results were similar (Figure 1D). Previous results thus do not really suggest that range is an important variable, but this issue certainly deserves to be investigated directly.

A second difference is that our task was synchronization, whereas the previous studies concerned reproduction (i.e., self-paced continuation tapping). This is an important difference, of course, although it is not clear why synchronization should lead to a USAR when continuation does not. Phase correction, which is required to maintain synchrony, could be involved somehow. Moreover, our auditory sequences contained perturbations for the purpose of assessing phase correction. These phase shifts may also have perturbed rhythm production in unexpected ways.

Finally, our participants were highly trained classical musicians, whereas earlier studies used participants with little or less music training. It is unclear why musicians should produce different and more systematic distortions of the 1:2 ratio than nonmusicians, and indeed Summers et al. (1986) found no significant difference between the rhythm production of two groups that differed in music training (Figure 1B). Nevertheless, it could be that professional-level musicians employ some special strategies in

[2] This was a concern of reviewers of our earlier paper (Repp et al., 2011) and in part motivated the present study. Note that sequential effects from one trial to the next (i.e., short-term shifts of the AR in the direction of the just-produced rhythm) would generate effects similar to that of an AR at the center of the range.

dealing with two-interval rhythms, such as mental subdivision of the long interval, that lead to a USAR.

Here we report three experiments. Experiment 1 addressed the potential role of the first two variables mentioned: the range of interval ratios, and synchronization versus continuation tapping in musicians. Experiment 2 investigated the role of music training, of auditory feedback during continuation tapping, and of the relative force of the two taps in the two-interval cycle. Experiment 3 examined whether the USAR arises in musicians' perception or production of two-interval rhythms and indirectly assessed the potential role of mental subdivision. In all three experiments, the interval ratios were presented at two tempi (cycle durations), to assess the generality of the findings. It will be seen that the results were generally clearer at the faster tempo.

Experiment 1

To explore the potential role of the range of interval ratios, Experiment 1 employed two relatively narrow, overlapping ranges, each of which included the 1:2 ratio. In the high range, the 1:2 ratio was below the center of the range, whereas in the low range it was above the center. If the mean ratio functions as the sole attractor, or as a second attractor in addition to the 1:2 ratio, a USAR should be obtained only in the high range, whereas a downward shift of the AR should be obtained in the low range. If the USAR has other causes but the mean ratio nevertheless serves as a secondary attractor, then the USAR should be less pronounced in the low than in the high range. To assess the difference between synchronization and self-paced reproduction, the experiment used a synchronization-continuation paradigm, and there were no perturbations in the rhythm template during synchronization. One might expect distortions in rhythm production to be more pronounced during continuation than during synchronization because production has to rely on memory, and there is no feedback about inaccuracies in the form of asynchronies between taps and tones of a rhythm template.

Experiment 1 differed in two additional respects from our previous study (Repp et al., 2011). First, tapping was bimanual (with the two hands alternating) rather than unimanual, which, according to Summers et al. (1989) and Semjen and Ivry (2001), should not make any difference. Second, the rhythm templates consisted of tones of different pitch in alternation, whereas previously they had been monotone. This, too, was expected to be irrelevant. Both predictions would be confirmed if the USAR was replicated under these conditions.

METHOD

Participants. The participants were 9 highly trained musicians, including 8 graduate students and one post-graduate of the Yale School of Music (6 women and 3 men, ages 22–26), and author BHR (age 65). The young musicians' primary instruments were piano (2), violin (4), viola, oboe, and bassoon, which they had studied for 13–21 years; BHR is a lifelong amateur pianist with 10 years of lessons in childhood. All participants but one considered themselves right-handed. Four individuals had been participants in the experiments of Repp et al. (2011) during the previous academic year.

Materials and equipment. Tone sequences were generated online 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 HD280 pro headphones. The tones had the pitches C4 (262 Hz) and D4 (294 Hz), the same nominal duration (40 ms, with rapid decay after the nominal offset), and the same intensity (MIDI velocity). The two pitches occurred in alternation, such that C4-D4 defined the short interval (i1), and D4-C4 defined the long interval (i2). Each sequence started with C4. Participants tapped on a Roland SPD-6 electronic percussion pad that they held on their lap. Finger impacts were audible as thuds whose loudness depended on individual tapping force, but the cushioned earphones attenuated this feedback considerably.

Each trial consisted of 23 cyclic presentations of a two-interval rhythm, followed by a silent interval equal to 20 times the cycle duration, which was terminated by a single tone, the signal to stop tapping. Two cycle durations (i1 + i2) were used, in separate blocks of trials: 810 ms and 1410 ms, referred to as fast and slow tempo, respectively. Two overlapping ranges of interval ratios were employed, referred to as high and low ranges. Each range comprised nine ratios, five of which (including 1:2) they had in common. The 1:2 ratio was the third-largest ratio in the high range but the seventh-largest ratio in the low range. The exact ratios and interval durations are shown in Table 1. The ratios for the two cycle durations were very similar and were treated as identical in statistical analyses.

Procedure. Participants completed four 1-hr sessions, two for each range condition. Sessions were typically one week apart. The two range conditions were run in a fixed order, high range followed by low range, with a different experiment (two weeks) intervening. In each session, participants completed three blocks of nine

TABLE 1. Range conditions (L = low, H = high), interval durations (i1, i2), and interval ratios (fractions) used in Experiment 1. Lines in italics pertain to Experiments 2 and 3.

Range	Cycle duration = 810 ms			Cycle duration = 1410 ms		
	Short (i1)	Long (i2)	Ratio	Short (i1)	Long (i2)	Ratio
L	234	576	0.406	410	1000	0.410
L	240	570	0.421	420	990	0.424
L	*246*	*564*	*0.436*	*430*	*980*	*0.439*
L	252	558	0.452	440	970	0.454
L/H	*258*	*552*	*0.467*	*450*	*960*	*0.469*
L/H	264	546	0.484	460	950	0.484
L/H	*270*	*540*	*0.500*	*470*	*940*	*0.500*
L/H	276	534	0.517	480	930	0.516
L/H	*282*	*528*	*0.534*	*490*	*920*	*0.533*
H	288	522	0.552	500	910	0.549
H	*294*	*516*	*0.570*	*510*	*900*	*0.567*
H	300	510	0.588	520	890	0.584
H	306	504	0.607	530	880	0.602

trials each at each of the two tempi. Half the participants started with the fast tempo condition in each session, whereas the other half started with the slow tempo condition. The nine trials in a block represented the nine different interval ratios and occurred in random order. In the course of the two sessions for each range condition, each participant thus experienced each individual rhythm six times.

Participants started a block by clicking a virtual button on the screen and then pressed the space bar to start each trial. They were instructed to start tapping with the third group of tones (i.e., with the fifth tone) and to tap in close synchrony with the tones. After the tones stopped, they were to continue tapping the rhythm at the same tempo without interruption until they heard the signal to stop tapping. At the end of each block, they saved their data in a file. In the first session participants were asked whether they would be comfortable tapping left-right to the two tones in each group, or whether they would prefer to tap right-left. Two participants (both right-handed) chose the latter option, which they were asked to maintain through all sessions.[3] All participants tapped on the upper left and upper right segments of the percussion pad, which had six segments arranged in two rows of three. The style of tapping was not prescribed. Some tapped by resting their hands on the pad and moving only their index or middle fingers, while others (the majority) tapped "from above" by moving their arms, as a percussionist would.[4]

Analysis. A small amount of data was lost due to technical problems.[5] For each participant, the means and standard deviations of short and long intertap intervals and of their sum (the tapping cycle duration) were computed within trials, separately for synchronization and continuation (omitting the first two tapping cycles in each case). Ratios of successive i1 and i2 intervals were computed within trials cycle by cycle, and these ratios were then averaged within and between trials representing the same rhythm. The within-trial standard deviation of ratios was also computed and averaged across trials representing the same rhythm. Statistical analyses consisted of repeated-measures ANOVAs with one or more of the following within-participant variables: range (high vs. low), tempo (fast vs. slow), task (synchronization vs. continuation), and ratio. The *p* values of all effects involving ratio (which had more than two levels)

[3] There was no reason to expect the order of hands to make a difference, and the results of the two participants who tapped right-left did not stand out in any way.

[4] This, incidentally, is another difference from our earlier study, where the majority of participants tapped by moving their finger only. No precise records were kept of participants' tapping styles.

[5] The problems were of two kinds: skipped trials, probably due to bounces of the space bar (a total of 28 out of 2,160 trials, or 1.3%), and individual taps that were too weak to be registered (120 out of about 172,800 expected taps, or 0.07%). Trials were of uneven length due to variable continuation tempo but typically contained about 80 taps. One participant tapped too lightly in the first session and was asked to repeat the session the following week.

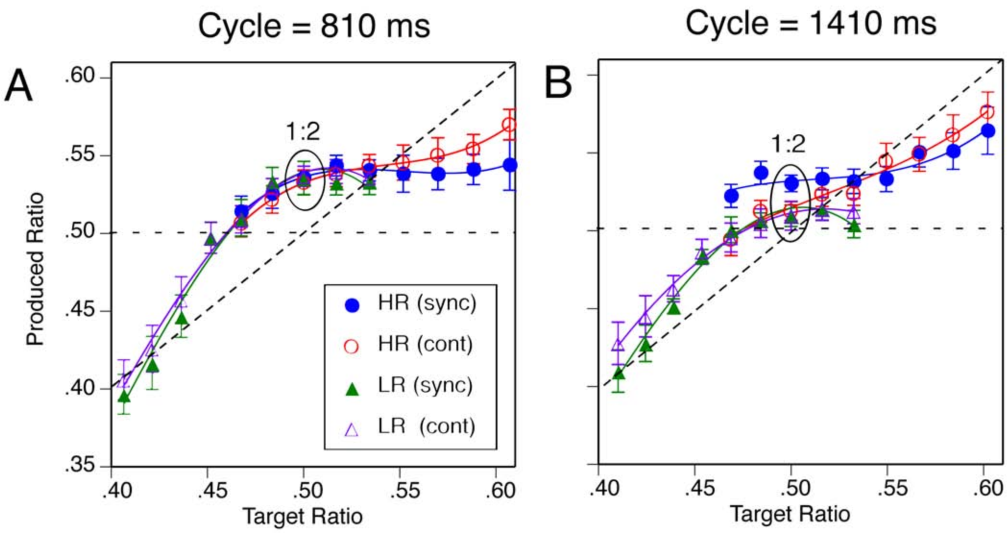

FIGURE 2. Ratio production results for synchronization and continuation in the two range conditions of Experiment 1: Mean produced ratio as a function of target ratio at the two tempi. The lines are cubic curve fits. Error bars represent ±1 standard error.

were subjected to the Greenhouse-Geisser correction, regardless of whether or not there was a significant deviation from sphericity.

RESULTS

Figures 2A and 2B show the mean produced interval ratio as a function of target ratio for synchronization and continuation in the two range conditions at the fast and slow tempi (separate panels). The lines are cubic functions, which happened to fit the data well. It is evident that the high-range and low-range data line up very well at the fast tempo and also quite well for continuation at the slow tempo. Only for synchronization at the slow tempo there seemed to be an effect of range. A 2 (tempo) × 2 (range) × 2 (task) × 5 (ratio) ANOVA on the five ratios shared by the two range conditions yielded a significant main effect of ratio, $F(4, 36) = 34.56$, $p < .001$, indicating that participants could differentiate the rhythms to some extent, even though they produced them rather similarly. This categorical tendency was quite pronounced and extended beyond the ratios shared by the two range conditions. The main effect of range was not significant, $F(1, 9) = 2.14$, $p = .177$. However, there was a significant main effect of tempo, $F(1, 9) = 7.85$, $p = .021$, and significant interactions between range and tempo, $F(1, 9) = 5.47$, $p = .044$, range and task, $F(1, 9) = 10.51$, $p = .01$, and range, tempo, and task, $F(1, 9) = 9.20$, $p = .014$. These interactions confirm the visual impression that range had an effect mainly on synchronization at the slow tempo.

The predicted USAR was clearly present in all conditions at the fast tempo, though it was smaller than in our previous study, suggesting an AR (where the functions cross the diagonal) in the vicinity of 0.53. A USAR was less evident at the slow tempo. This was confirmed by two-tailed t-tests that examined whether production of the 1:2 ratio differed significantly from a fraction of 0.5. These tests were significant, $t(9) \geq 3.17$, $p \leq .011$, for all four conditions at the fast tempo, but only for synchronization in the high range at the slow tempo, $t(9) = 5.50$, $p < .001$. The test approached significance for continuation in the high range at the slow tempo, $t(9) = 2.09$, $p = .067$.

A 2 (tempo) × 2 (task) × 9 (ratio) ANOVA on the complete data for the high range condition revealed, besides an obviously significant main effect of ratio, only a significant Task x Ratio interaction, $F(8, 72) = 9.23$, $p = .001$. Contrary to expectations, production of the rhythms was relatively more accurate (less categorical) in continuation than in synchronization, which means that the line connecting the data points for continuation had a steeper slope. However, no rhythm except the one closest to the AR was produced accurately; all showed the characteristic distortion towards the AR, at both tempi.

An analogous ANOVA on the complete data for the low range condition yielded, besides the obviously significant main effect of ratio, only a marginally significant main effect of task, $F(1, 9) = 5.32$, $p = .047$, due to produced ratios being somewhat larger during continuation than during synchronization, mainly when the ratio was small. The Task × Ratio interaction, $F(8, 72) = 2.48$, $p = .092$, did not reach significance, nor did the Tempo × Ratio interaction $F(8, 72) = 2.70$, $p = .085$. Ratios with fractions larger than 0.45 showed substantial enlargement in production (i.e., attraction towards the AR), whereas the smallest ratios were produced fairly accurately on average but showed large individual differences (reflected in large standard errors).

There was also a tendency for the smallest within-trial variability to occur at a ratio somewhat larger than 1:2. These data are presented in the Appendix (accessible at http://www.haskins.yale.edu/staff/repp.html), where also information about the tempo of continuation tapping can be found.

DISCUSSION

The results of Experiment 1 show that the USAR found by us previously (Repp et al., 2011) was not due solely to the range of ratios employed. Although range had some limited effects on rhythm production, and these effects were in the expected direction, they merely reduced the USAR; there was no downward shift of the AR in the low range conditions. This suggests that the USAR has a different cause that outweighs any attraction to the mean ratio.

The results of Experiment 1 also show that the USAR is not specific to synchronization, at least at the fast tempo. At the slow tempo, the USAR was reliable only in synchronization. This is surprising because we expected the effect to be larger in continuation, when tapping is not constrained by an exact auditory template. However, rhythm production was generally more accurate and less variable in continuation than in synchronization, at both tempi. Evidently, the perceptual feedback provided by asynchronies was of little help, and the requirement of phase correction in synchronization probably accounts for the greater variability in that task.

The USAR observed at the fast tempo was only about half as large as the one in our earlier study. One difference between the studies is that tapping was bimanual rather than unimanual. Although this should have made little difference according to the literature (Semjen & Ivry, 2001; Summers et al., 1989), differences in preferred tapping style may have played a role: The majority of the present participants moved their arms rather than just the fingers, which perhaps increased their accuracy. Two other differences between the two studies—the presence versus absence of perturbations in the rhythm templates and monotone versus alternating-pitch sequences—seem unlikely causes of a difference in results and in any case pertain to synchronization only. Of course, the difference in the magnitude of the USAR could just be a group difference, as the participants were partially different, and some of the present participants had exceptional rhythmic acuity.

Experiment 1 replicated the basic finding that ratios smaller than the AR are increased in production, whereas those larger than the AR are reduced. However, ratios in the vicinity of 0.42 did not show assimilation, on average. A possible reason for this is the existence of another attractor at 1:3 (= 0.33). Such a secondary AR would not be implausible in highly trained musicians, for whom 1:3 (sixteenth note and dotted eighth note) is a very familiar nominal ratio. However, a recent study that involved the same participants (Repp, 2011) yielded no evidence for an attractor at 1:3. Rather, production of small interval ratios was simply rather accurate, on average.

As reported in the Appendix, Experiment 1 also provided evidence that the variability of ratio production decreases in the vicinity of the AR, which is consistent with many findings in the dynamic systems literature that show greater stability of rhythmic movement near an attractor (e.g., Tuller & Kelso, 1989; Yamanishi, Kawato, & Suzuki, 1980). The attractor in those studies, however, usually corresponds to 1:1, namely anti-phase movement of the two hands. That attractor played no role in the present study because none of the interval ratios was close to 1:1, and participants knew that the two intervals had to be different.

All participants showed greater ratio variability at the fast than at the slow tempo, even though variability of the intervals themselves must have been larger at the slow tempo, according to the general rule that variability increases with duration. We did not pursue this interesting result further. One possible cause is greater compensation (i.e., a negative correlation) between the two intervals in order to maintain a constant cycle duration at the fast tempo.

Experiment 2

Although Experiment 1 replicated the USAR and thereby showed that the USAR was not critically dependent on certain methodological variables (range of interval ratios, tapping mode), it did not reveal what causes the effect and why we find a USAR while other studies found a downward shift of the AR, if any. One remaining difference among the studies concerns the extent of music training of the participants. Although Summers et al. (1986) had not found any effect of music training, their musically trained participants were not professional-level musicians like the present participants (author BHR excepted, who instead has many decades of experience as a musical amateur). Experiment 2 addressed this issue by testing both musicians and nonmusicians.

Having used a continuation task in Experiment 1, another difference in procedure came to our attention. In the experiments of Povel (1981) and Summers et al.

(1986, 1989), the continuation taps "produced" feedback sounds that matched the sounds that had conveyed the target rhythm, so that there was perceptual continuity between listening (during which tapping along was encouraged) and reproduction. In our Experiment 1, however, the taps did not control any feedback tones; they only produced impact thuds on the tapping pad. Thus the auditory feedback was perceptually different from the target rhythm. Obviously, this cannot explain why a USAR occurred during synchronization, but Povel and Summers et al. did not investigate synchronization, and in all fairness we thought we should try to replicate their conditions as closely as possible. Therefore, in Experiment 2 we added feedback tones during continuation tapping.

Furthermore, Experiment 2 included an analysis that addressed an important hypothesis about a possible cause of the USAR. It is known that varying the relative force of taps affects their timing: The interval following an accented tap is typically lengthened, while the preceding interval may either be shortened or lengthened, depending on tempo (Billon & Semjen, 1995; Billon, Semjen, & Stelmach, 1996; Piek, Glencross, Barrett, & Love, 1993; Semjen & Garcia-Colera, 1986; Semjen, Garcia-Colera, & Requin, 1984). Could it be that the USAR is caused by intensity differences between the taps?

In order to give rise to a USAR, the tap preceding the short interval (i1) would have to be accented, thereby lengthening i1 and increasing the i1/i2 fraction. However, it is common to perceive the second event in a group of two as accented (Povel & Okkerman, 1981), and consequently the metrical accent (the "beat") also tends to be located on the second element. Thus it seems unlikely that the first tap would be stronger than the second, and this argues a priori against the hypothesis. Nevertheless, it was important to address this issue with measurements of relative tap force, and we did this using a subset of the data of Experiment 2.

In a further effort to match the methods of earlier studies, we reverted to monotone rhythm templates during synchronization. A single range of ratios was used, centered on 1:2. We ran one group of musicians and then two groups of nonmusicians. The first group of nonmusicians was inadvertently instructed to tap unimanually, whereas the musicians had tapped bimanually. Although this should not make a difference according to earlier findings (Semjen & Ivry, 2001; Summers et al., 1989—see Figure 1C), we nevertheless decided to run a second group of nonmusicians who tapped bimanually.

METHOD

Participants. The musician group consisted of 8 of the participants from Experiment 1 (one violinist and the bassoonist were no longer available) plus one additional music student (a cellist). The first nonmusician group consisted of 12 individuals (7 women, 5 men, ages 21–27), mostly students, who were recruited from the subject pool of the Max Planck Institute for Human Cognitive and Brain Sciences in Leipzig, Germany, subject to the requirement that they should have no more than 4 years of training on a musical instrument. Six of them reported no active music experience; two had played one or two instruments for a total of 4 years; four (including one of the instrumentalists) had engaged in singing and/or dancing for 5–7 years; and one had been a rapper for 2–3 years. The second nonmusician group was tested at Carleton College in Northfield, Minnesota. This group consisted of 12 older individuals (2 women, 10 men, ages 43–77) from the local community who were recruited by word of mouth. They all had at least a college degree, and 7 of them were members of a running club. None of them had any formal music training, but all enjoyed listening to music. Two identified themselves as left-handed. The data of one Northfield participant were omitted after analysis because he produced unprecedentedly large interval ratios (fractions near 0.70) at the slow tempo but the smallest ratios (fractions around 0.40) at the fast tempo.

Materials and equipment. The structure of the synchronization-continuation trials was the same as in Experiment 1. All tones had the pitch C4, and continuation differed from synchronization only in that the tones were controlled by the participants' taps rather than by the computer, a task also known as pseudo-synchronization (Flach, 2005; Fraisse & Voillaume, 1971). Due to electronic processing delays, the feedback tones lagged by about 15 ms behind the taps, which was imperceptible. The five target interval ratios were the ones shown in italics in Table 1. They ranged from 0.44 to 0.57 and thus were almost exactly centered on 0.5, which was also the central target ratio. As in Experiment 1, there were two cycle durations, 810 ms and 1410 ms.

The equipment for the musicians was the same as in Experiment 1. That for the nonmusicians was almost identical, differing only in that a Yamaha Clavinova CLP-150 digital piano was used for tone generation in Leipzig, whereas the internal DSL synthesizer of the computer (with piano timbre) was used in Northfield. In addition to the times of taps, their MIDI velocities were recorded. MIDI velocities are monotonically related to force of impact.

Procedure. Each participant completed five blocks of five trials at each of the two tempi in a single 1-hr session, with the order of the two tempi counterbalanced across participants. Participants were informed that control of the tones would change from the computer to themselves at some point, but that it did not matter if and when they realized this (cf. Repp & Knoblich, 2007, where this was the question of interest). They were told that there were five different rhythms and that they should maintain the exact rhythm throughout each trial. Musicians tapped with alternating hands, left-right in all cases but one. The Leipzig nonmusicians tapped unimanually with their preferred hand. The Northfield nonmusicians tapped with alternating hands, 7 of them left-right and 3 right-left; one switched during the experiment.

Analysis. A small amount of data was lost to analysis for various reasons.[6] The methods were similar to those in Experiment 1.

RESULTS[7]

Ratio production. The results for the musicians are shown in Figures 3A and 3B. In a 2 (tempo) × 2 (task) × 5 (ratio) ANOVA, all effects except the Task x Tempo interaction were significant. Ratios were generally more distorted in synchronization than in continuation, and the plateau indicating a categorical tendency was at larger ratios at the fast tempo than at the slow tempo, indicating a greater USAR. A 2 (tempo) × 2 (task) ANOVA on the data for the 1:2 ratio alone, however, revealed only a significant main effect of task, $F(1, 8) = 19.31$, $p = .002$, not of tempo, $F(1, 8) = 3.03$, $p = .12$, and no interaction. *T*-tests on the 1:2 ratio data in each condition confirmed that there was a significant USAR in synchronization at the fast tempo, $t(8) = 5.82$, $p < .001$, and at the slow tempo, $t(8) = 3.44$, $p = .009$. The USAR also reached significance in continuation at the fast tempo, $t(8) = 2.54$, $p = .035$, but not in continuation at the slow tempo, $t(8) = 1.35$, $p = .214$.

Figures 3C and 3D show the results for the Leipzig nonmusicians (tapping unimanually), which were very different and also showed much larger individual differences (standard error bars). The overall ANOVA revealed a significant main effect of ratio, $F(4, 44) = 6.67$, $p = .002$, as well as a main effect of tempo, $F(1, 11) = 7.45$, $p = .020$. Although the functions were very flat, they reflect some sensitivity to the differences among the rhythms. The produced ratios were substantially lower at the fast than at the slow tempo, with a downward shift of the AR indicated at the fast tempo. The ANOVA on the data for the 1:2 target ratio again showed the main effect of tempo to be significant, $F(1, 11) = 6.53$, $p = .027$. The large *downward* deviation from 0.5 at the fast tempo reached significance only in continuation, $t(11) = -2.75$, $p = .019$, not quite in synchronization, $t(11) = -2.12$, $p = .058$, due to large individual differences. There was no significant deviation at the slow tempo.

Figures 3E and 3F show the results of the Northfield nonmusicians (tapping bimanually). They, too, showed very flat functions and even larger individual differences. The function for synchronization at the slow tempo actually had a negative slope, reflecting an inability to distinguish the rhythms. The overall ANOVA yielded no significant main effect of ratio but a Ratio × Task interaction, $F(4, 40) = 6.45$, $p = .002$. The triple interaction merely approached significance, $F(4, 40) = 2.55$, $p = .073$. There was no significant effect in the ANOVA on the data for the 1:2 ratio, and no deviations from 0.5 were significant in *t*-tests.

Pairwise statistical comparisons of the three participant groups were conducted using mixed-model 2 (group) × 2 (tempo) × 2 (task) ANOVAs on the data for the 1:2 ratio. Musicians produced significantly larger ratios than did the Leipzig nonmusicians, $F(1, 19) = 8.62$, $p = .008$, and this difference interacted with tempo, $F(1, 19) = 8.07$, $p = .010$, because it was much more pronounced at the fast tempo. The main effect of task was also significant, $F(1, 19) = 8.94$, $p = .008$, because ratios were higher during synchronization than during continuation in both groups. There was no significant overall group difference between the musicians and the Northfield nonmusicians, $F(1, 18) = 0.62$, $p = .443$. In this comparison only the Group x Task interaction was significant, $F(1, 18) = 5.19$, $p = .035$, because only the musicians showed larger ratios during synchronization than during continuation. The overall difference between the two nonmusician groups was almost significant, $F(1, 21) = 4.05$, $p = .057$, because the Northfield group produced larger ratios than the Leipzig group. In this comparison only the main effect of tempo reached significance, $F(1, 21) = 4.40$, $p = .048$, because ratios generally were larger at the slow than at the fast tempo

[6] For musicians, the amount of data lost due to skipped trials (5/450 = 1.1%) and missed taps (34/36,000 = 0.09%) was minimal. For the Leipzig nonmusicians, the loss due to skipped trials was similarly small (5/600 = 0.8%), but losses due to unusually long intertap intervals were more frequent (380/48,000 = 0.8%). Some of these unusually long intervals were due to weak taps that failed to be registered, but the majority appeared to be due to hesitations that punctuated especially the continuation phase at the slow tempo and occurred much more often in the long (between-group) interval than in the short interval of the rhythm. Such exceptionally long intervals were deleted as outliers during data inspection by author BHR because they would have distorted the mean interval ratio. (Without such editing, the produced ratios for slow continuation would have been somewhat *smaller* than reported, and variability would have been greater.) The Northfield nonmusicians had no skipped trials, but three trials were considered unusable due to missing taps (3/550 = 0.5%), and a substantial number of exceptionally long intervals due to missing taps and hesitations (662/44,000 =1.5%) were edited out.

[7] See the Appendix for results regarding the tempo of continuation tapping.

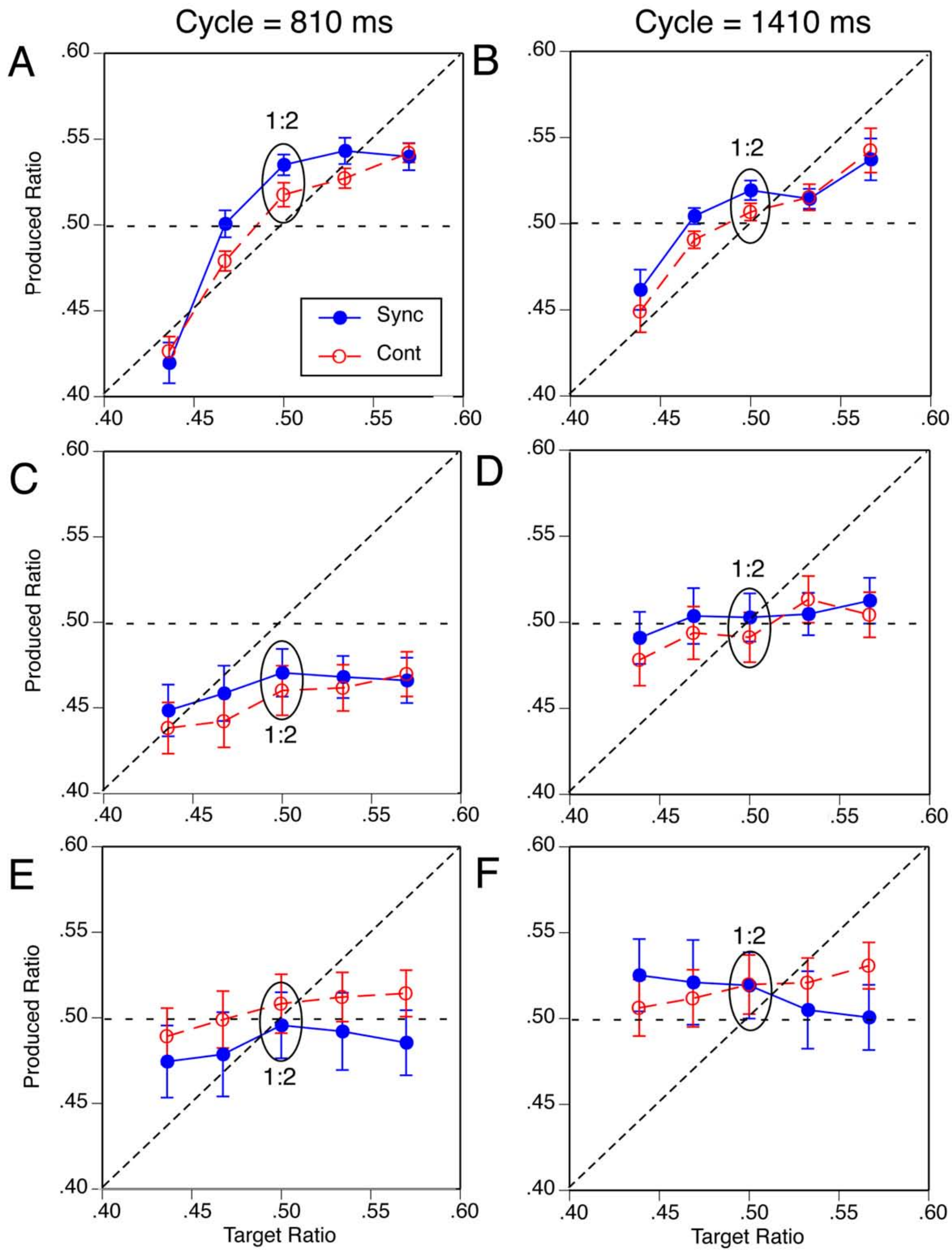

FIGURE 3. Mean ratio production during synchronization and continuation at fast and slow tempi in Experiment 2: (A, B) Musicians. (C, D) Leipzig nonmusicians. (E, F) Northfield nonmusicians. Error bars represent ±1 standard error.

in both groups. Thus, these comparisons are somewhat compromised by the large individual differences among nonmusicians. While some of them had results suggesting a USAR, the main point to note is that only nonmusicians ever showed substantial individual downward shifts of the AR.

Relative tap intensities. Figure 4 shows the mean produced ratios for the 1:2 target ratio at the two tempi as a function of the mean MIDI velocity difference between the second and first taps in the rhythmic group, averaged over synchronization and continuation, for each of the three groups of participants. The first thing to note is that the Leipzig nonmusicians had a much narrower range of tap intensity differences than the other two groups. This difference is clearly due to the use of one hand versus two. Second, and somewhat surprisingly, neither of the two groups that tapped bimanually showed a general tendency to accent the second tap. The intercepts of the regression lines are estimates of the ratios that would be produced with equally intense taps, and they are similar to the mean ratios obtained for the 1:2 target ratio (cf. Figure 3). This indicates that the mean produced ratios were not a consequence of predominant tendencies to accentuate one or the other tap. Interestingly, accentuation did seem to have an effect on the produced ratio, which is suggested by the uniformly positive correlations in Figure 4, but the direction of the effect was the opposite of what had been expected: The more the second tap was accented, the larger was the produced ratio. This implies that the long interval (i2) was shortened by accentuation of the preceding tap, and/or that the short interval (i1) preceding the accented tap was lengthened. Even the Leipzig nonmusicians seemed to show the same effect of accentuation despite their severely restricted range of MIDI velocity differences between taps. Only one of the six individual correlations reached significance, however.

DISCUSSION

Experiment 2 replicated the USAR for musicians, at least at the faster tempo. Adding feedback tones during continuation seemed to make no difference. Likewise, elimination of pitch variation in the rhythm templates during synchronization did not change the USAR substantially relative to Experiment 1. However, the experiment did reveal a variable that played a significant role, namely music training. Nonmusicians were not only significantly more inaccurate and variable than musicians, but as a group they did not show a significant USAR. On the contrary, quite a few individuals showed a large downward shift of the AR at the fast tempo, consistent with previous results by Summers et al. (1989). Given that Summers et al. (1986) did not find any effect of moderate music training, it may be that the USAR is specific to highly trained (perhaps only classically trained) musicians. However, there was clearly overlap between the musician and nonmusician groups, with some nonmusicians showing a USAR.[8]

The Northfield group of nonmusicians was more similar to the musicians in some respects than was the Leipzig group of nonmusicians. There were three differences between the two nonmusician groups that could have played a role. First, tapping was unimanual in Leipzig but bimanual in Northfield, which could have made a difference despite preceding results to the contrary (Semjen & Ivry, 2001; Summers et al., 1989). Note, however, that Repp et al. (2011) found a *larger* USAR for musicians tapping unimanually than for the present musicians who tapped bimanually. So, if anything, unimanual tapping might increase the USAR and therefore is unlikely to account for the contrary results of the Leipzig group. Second, the Northfield group was considerably older than the Leipzig group. Third, the groups represented different cultural backgrounds. It was beyond the scope of the present research to explore these variables further.

Experiment 2 also helped rule out one potential explanation of the USAR, namely that it was an artifact of accenting the tap that preceded the short interval. Although some individual participants who tapped bimanually gave greater force to that tap, others favored the other tap. On the whole, neither musicians nor nonmusicians had a general preference for accenting one or the other tap, and the results for the hypothetical situation of equally strong taps were close to the average group results. Participants who tapped unimanually treated the two taps rather equally. We have no explanation for the surprising tendency suggesting that the interval preceding (rather than the following) a relatively accented tap was lengthened, but this is a separate issue that need not detract us here from our pursuit of the possible causes of the USAR in musicians.

Experiment 3

The main purpose of Experiment 3 was to address the question of whether the USAR in musicians arises in rhythm perception or production. Our earlier study on two-interval rhythm production (Repp et al., 2011) included a purely perceptual condition in which

[8] The significance of such deviations at the individual level was not assessed, although it could be done in principle by using the variability across trial blocks or even within trials.

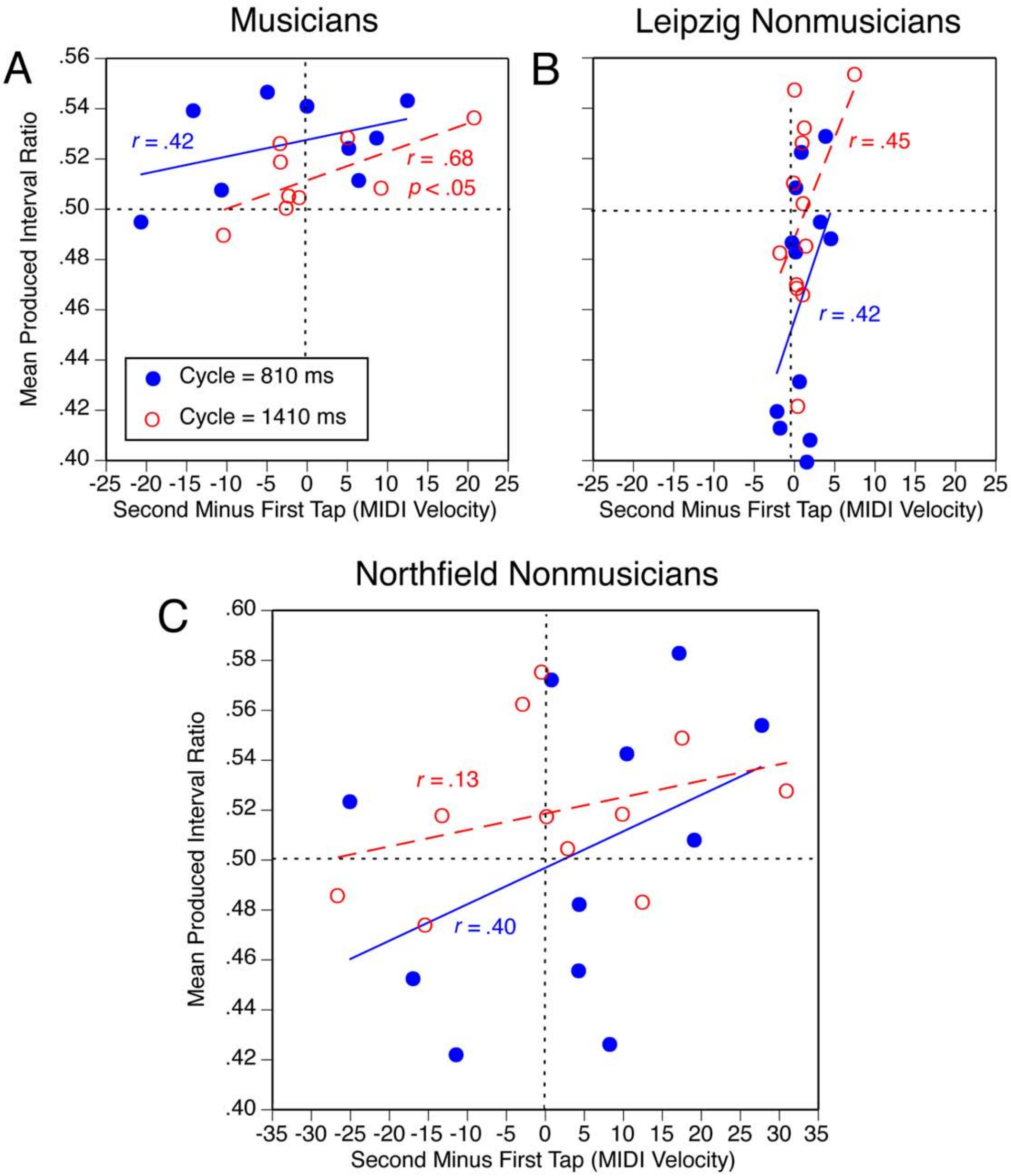

FIGURE 4. Mean produced interval ratio for the 1:2 target ratio (horizontal dotted line) for (A) musicians, (B) Leipzig nonmusicians, and (C) Northfield nonmusicians in Experiment 2 as a function of the MIDI velocity difference between the second and first taps in the rhythmic group. Each data point represents an individual participant. Regression lines and corresponding correlations are shown.

participants were required to detect phase shifts (i.e., single lengthened or shortened intervals) in the rhythm sequences. The results of this task revealed significant asymmetries in detection, such that phase shifts that changed the local interval ratio in the direction in which it was typically distorted in production (i.e., towards the AR) were more difficult to detect than phase shifts that distorted the local interval ratio in the opposite direction. Moreover, the perception results suggested an AR fraction larger than 0.5. Thus there was a close parallel between the perception and production results, which led us to hypothesize that the observed ratio distortions originate in perception, with production merely conforming to perception.

To test this hypothesis, Experiment 3 included three conditions in which the long interval was subdivided in either perception or production, or in both. This subdivision transformed a two-interval rhythm (i1, i2) into a three-interval rhythm (i1, i2a, i2b; i.e., a rhythm having three, not necessarily different, intervals per cycle). In the M2T3 condition (two **M**etronome tones and three **T**aps per cycle), participants listened to a two-interval rhythm during synchronization but produced a three-interval rhythm by making an extra tap during the long interval; subsequently, they continued tapping that three-interval rhythm. If the USAR arises in perceptual distortion of a two-interval rhythm, it should be present in that condition because the extra tap simply subdivides the long interval that has already been perceived and stored in memory in a distorted form.[9] Conversely, in the M3T2 condition, participants listened to a three-interval rhythm during synchronization but made only two taps and then continued tapping that two-interval rhythm. If the USAR arises in production of a two-interval rhythm, it should be evident in that condition.[10] In the third condition, M3T3, participants synchronized three taps with a three-interval rhythm and also continued to tap a three-interval rhythm. We had no specific predictions for that condition, which was included as a logical extension of the other two conditions and as a preliminary investigation of three-interval rhythm production, the detailed results of which are reported in the Appendix.

By introducing subdivision of the long interval, Experiment 3 also addressed the possibility that the USAR in previous experiments may have been due to mental subdivision of the long interval, not an unlikely strategy with musicians since 1:2 and similar ratios can be interpreted as being in a triple meter (i.e., underlyingly isochronous). Mental subdivision, like explicit subdivision by means of a tap, may make the long interval seem longer and thus may lead to its compensatory shortening in production (Repp & Bruttomesso, 2009), which may be evident as a USAR. If so, the USAR should be enhanced when the subdivision is explicit rather than just imaginary, which is the case in condition M2T3.

[9] Admittedly, there may also be perceptual feedback from one's own productions that could affect future productions. However, because there is evidence that subdivided intervals are perceived as being longer than empty intervals (Repp, 2008), this feedback might lead to a compensatory relative shortening of the long interval in production (Repp & Bruttomesso, 2009), which would increase the interval ratio and thus also the USAR.

[10] Here, the USAR might be attenuated or canceled if the long interval is perceived as lengthened due to external subdivision and therefore is also lengthened in production.

METHOD

Participants. The same participants as in Experiment 1 participated, except for one violinist who was no longer available. She was replaced by a cellist from the Yale School of Music, who had similarly extensive training. This group differed from the musician group of Experiment 2 only in that the bassoonist was still included.[11]

Equipment and materials. The equipment was the same as previously. The rhythm templates were similar to those of Experiment 1 in that different pitches (C4 and D4) were used for the tones delimiting the short and long intervals. In the M3 conditions, a third tone was played exactly in the middle of the long interval during synchronization. The pitch of that tone was A3 (220 Hz), and it was of the same duration and intensity (MIDI velocity) as the other tones. The two cycle durations and five interval ratios were the same as in Experiment 2.

Procedure. Participants completed three one-hour sessions, one for each of the three conditions (M3T2, M2T3, M3T3), typically one week apart. The order of the three conditions was approximately counterbalanced across participants.[12] Within a session, half the participants started with the fast tempo, the other half with the slow tempo. At each tempo, they completed five blocks of five trials each, which represented the five interval ratios, presented in a random order.

In the M3T2 condition, participants were instructed to tap with hands alternating left-right (eight participants) or right-left (preferred by two participants) in synchrony with the tones C and D while ignoring A, and to continue tapping this rhythm at the same tempo after the auditory sequence had ended. In the M2T3 condition, they were told to tap left-right-right or right-left-left, respectively, with the first two taps being synchronized with the tones C and D, and the third tap subdividing the long interval, in whichever way they considered most comfortable. That exact rhythm was then to be continued after the end of the pacing sequence. In the M3T3 condition, they were told to tap similarly in synchrony with the three tones and to continue tapping that rhythm. There were no feedback tones during continuation tapping.

[11] Experiment 3 actually preceded Experiment 2, but the order is reversed here for expository reasons.

[12] Two participants had to repeat the M2T3 session the following week, one because his third tap had often been too weak to be registered, the other one because she had misunderstood the instructions and, instead of adopting the presented rhythm and merely subdividing i2, had tapped (almost) isochronously with all rhythms.

RESULTS[13]

Figure 5 shows the ratio production results for the three conditions at the two tempi, with the results for the 1:2 target ratio highlighted (ovals). The main result is immediately clear: A USAR was obtained in the M3T2 condition, but not in the M2T3 and M3T3 conditions. A 3 (condition) × 2 (tempo) × 2 (task) ANOVA on the data for the 1:2 target ratio confirmed a significant difference among conditions, $F(2, 18) = 24.92$, $p < .001$, as well as a main effect of tempo, $F(1, 9) = 16.85$, $p = .003$, and a marginally significant Condition x Tempo interaction, $F(2, 18) = 3.94$, $p = .042$. These effects were due mainly to the M3T2 condition, as a 2 × 2 × 2 ANOVA on the 1:2 ratio data of the M2T3 and M3T3 conditions alone yielded no significant results. A 2 × 2 ANOVA on the 1:2 ratio data of the M3T2 condition alone confirmed a main effect of tempo, $F(1, 9) = 20.14$, $p = .002$. In the M3T2 condition, the produced 1:2 ratio was significantly larger than 0.5 in synchronization, $t(9) = 5.39$, $p < .001$, and continuation, $t(9) = 6.94$, $p < .001$, at the fast tempo. However, it was also significant, albeit smaller, in synchronization, $t(9) = 3.31$, $p = .009$, and continuation, $t(9) = 2.56$, $p = .031$, at the slow tempo. In the M2T3 and M3T3 conditions (eight *t*-tests), there was only one significant deviation from 0.5, in synchronization at the slow tempo in the M3T3 condition, $t(9) = –2.88$, $p = .018$, and it was in the opposite direction.

The pattern of responses to the five interval ratios showed some interesting differences among conditions and also in comparison with Experiment 2 (Figures 3A and 3B). The response functions for the M3T2 and M3T3 conditions were fairly similar, but those in the M3T3 condition were lower. This was confirmed in a 2 (condition) × 2 (tempo) × 2 (task) x 5 (ratio) ANOVA on the M3T2 and M3T3 conditions, which showed the main effect of condition to be significant, $F(1, 9) = 17.43$, $p = .002$. There was also a significant Condition x Tempo interaction, $F(1, 9) = 11.17$, $p = .009$, because the difference was more pronounced at the faster tempo, whereas the Condition x Ratio interaction was far from significance. Ratio, besides having an obvious main effect, interacted somewhat with tempo, $F(4, 36) = 3.96$, $p = .035$, and task, $F(4, 36) = 4.88$, $p = .023$. Comparisons of the M2T3 condition with either of the other two conditions yielded a number of significant differences that need not be detailed here. Only the Condition x Ratio interaction for M2T3 versus M3T3, $F(4, 36) = 17.44$, $p < .001$, should be mentioned, as it confirms the different shapes of the response functions in these two conditions, especially for ratios larger than 1:2.

DISCUSSION

The main result of Experiment 3 is clear: The USAR was obtained only in the M3T2 condition, where participants actually tapped a two-interval rhythm. The magnitude of the effect was similar to that observed in Experiments 1 and 2, which means that exact bisection of i2 by an additional tone had little effect on the produced i1:i2 ratio. It should be noted that participants heard a perfectly isochronous rhythm template (i1 = i2a = i2b) during synchronization when the presented i1:(i2a + i2b) ratio was 1:2; nevertheless, they increased that ratio in production. If explicit subdivision of i2 by the additional tone had increased the subjective duration of i2, the 1:2 ratio should have been reduced in production, contrary to the observed USAR. If such an effect occurred, it was smaller than the USAR, which must have a different cause.

There was no USAR when i2 was subdivided by an additional tap, regardless of whether an additional tone was present (M3T3) or not (M2T3) during synchronization, even though an effect of the tap on the subjective duration of i2 could have led to a USAR in the M2T3 condition. Active subdivision of i2 by an additional tap, even if it was not exact bisection (see Appendix), enabled participants to produce the 1:2 ratio accurately.

The findings of Experiment 3 suggest that, contrary to the hypothesis based on our earlier findings (Repp et al., 2011), the USAR arises in production, not in perception, of two-interval rhythms. This suggests that the perceptual asymmetries found in our earlier study, where participants had to detect small phase shifts in rhythmic sequences, were not the cause of the ratio distortions in rhythm production. On the contrary, it may be that the production patterns are primary and have an impact on perception of interval ratios, perhaps through internal motor simulation while listening to a rhythm (cf. Bengtsson et al., 2009).

Experiment 3 also addressed the possibility that the USAR in Experiments 1 and 2 was due to mental subdivision of the long interval (i2). Mental subdivision should have effects similar to overt subdivision by a tap, only smaller (cf. Repp, 2010). However, there was no USAR in the M2T3 condition, where a tap subdivided the long interval. Therefore, mental subdivision is not likely to have caused the USAR in earlier experiments.

[13] See the Appendix for results regarding the tempo of continuation tapping and the temporal placement of the subdivision tap in the M2T3 and M3T3 conditions.

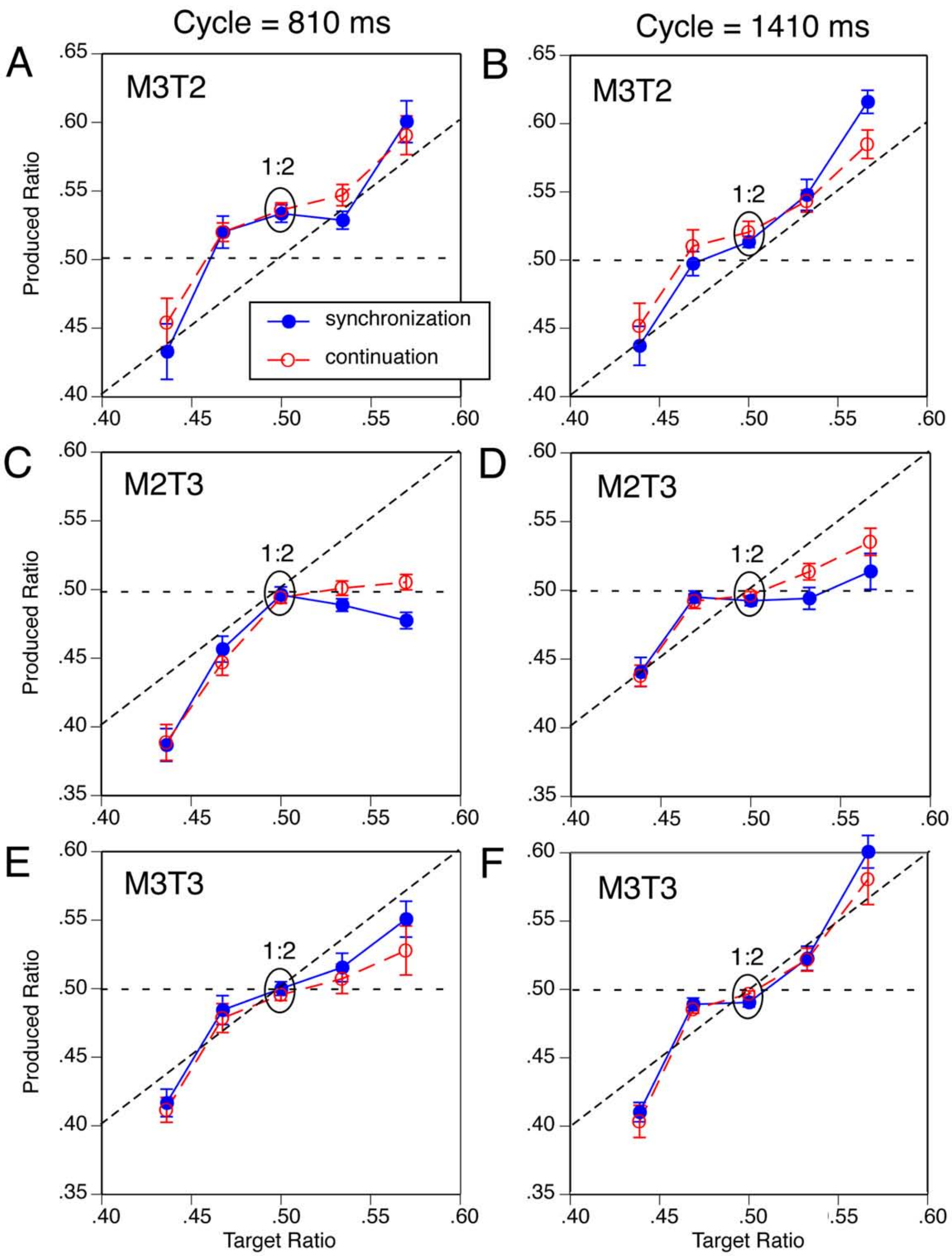

FIGURE 5. Ratio production results for synchronization and continuation in the three conditions of Experiment 3 at two tempi. (A, B) M3T2 condition. (C, D) M2T3 condition. (E, F) M3T3 condition. Error bars represent ±1 standard error.

General Discussion

This study was motivated by the unexpected finding of an upward shift of the attractor ratio (USAR) in musicians' synchronization with two-interval rhythms (Repp et al., 2011). This USAR contrasted with tendencies toward a downward shift observed in earlier studies (Povel, 1981; Summers et al., 1986, 1989). Three experiments investigated possible causes of the USAR in musicians. While replicating the effect, Experiment 1 showed that it was not due to the range of interval ratios used, although range had some effect on synchronization at a relatively slow tempo. Experiment 1 also showed that the USAR was not specific to synchronization with a rhythm template; at a fast tempo, the USAR was equally large in synchronization and continuation, though it was smaller in continuation than in synchronization at a slower tempo. Interestingly, tapping without a guiding rhythm template did not increase the USAR; if anything, the USAR decreased in continuation tapping. Experiment 1 also showed that the USAR does not depend on rhythmic tapping being unimanual, as it was replicated with bimanual tapping, although it was somewhat reduced in magnitude.

Experiment 2 showed that the USAR in musicians persists, at least at a fast tempo, if feedback tones are present during continuation. The experiment also demonstrated that the USAR was not due to preferential accentuation of one of the two taps in the rhythm cycle. Although accentuation (if small and probably unintended intensity differences can be called that) appeared to have some effect on rhythm production, this effect was in an unexpected direction (shortening of the preceding interval) and independent of the USAR. The major finding of Experiment 2, however, was that nonmusicians did not show a USAR, on average. Although individual differences were large among nonmusicians, quite a few of them showed a pronounced downward shift of the AR at the fast tempo. This is consistent with previous studies in the literature (Povel, 1981; Summers et al., 1986, 1989). Although some individual nonmusicians showed a USAR, only highly trained (classical) musicians showed a USAR consistently.

Experiment 3 suggested that the USAR arises in production of a two-interval rhythm, not in its perception. This was unexpected given the perceptual results of our previous study (Repp et al., 2011). Musicians who listened to a two-interval rhythm template but produced a three-interval rhythm by making an extra tap during the long interval did not show any USAR. This result also suggested that mental subdivision of the long interval was not the cause of the USAR in the preceding experiments.

Thus we have been able to rule out a number of possible explanations of the USAR, though we have not yet found its actual cause. Since two-interval rhythms with ratios in the vicinity of 1:2 can be perceived as being in a triple meter, it may be that the USAR has something to do with triple as opposed to duple meter. Triple meter is less common than duple meter and sometimes causes difficulties in perception or production (e.g., Bergeson & Trehub, 2006; Drake, 1997; Repp, 2003, 2007). However, these difficulties usually beset nonmusicians and should be minimal in musicians who have extensive experience with triple meter. Another line of explanation might be based on the observation that, in two-interval rhythms, the grouping accent and hence the metrical beat is usually located on the second tap of the rhythmic group (Povel & Okkerman, 1981), with the first tap serving as an upbeat. This could lead to the first tap being attracted to the second tap, thereby creating increased "forward motion" of the rhythm, as was suggested recently by Butterfield (2011) in an attempt to explain the swing rhythm in jazz performance. Note, however, that this process would lead to the opposite of the USAR: a shortening of the short interval, which *reduces* the interval ratio. Also, the swing rhythm is nominally even (i.e., two eighth notes in musical notation), whereas a 1:2 rhythm is nominally uneven (i.e., an eighth note and a quarter note if notated) and already possesses forward motion before it is distorted. The USAR actually reduces forward motion.

In all three experiments, the USAR was more pronounced and more consistent at a fast than at a slow tempo of rhythm production. This makes intuitive sense because a rhythm is less "tight" and coherent when it is slowed down. It may also be noted (see Table 1) that, at the slow tempo, both i1 and i2 were both longer than 400 ms, whereas at the fast tempo i1 was always shorter than 400 ms while i2 was longer than 400 ms. Fraisse (1956) drew a distinction between "short" and "long" intervals, with the boundary being around 350 ms, and attributed different functions to them, with the former separating events within a rhythmic group and the latter separating rhythmic groups. Thus the rhythmic grouping (if any) was weaker at the slow tempo in our experiment, and this seemed to attenuate the USAR. It is possible that the slow rhythms were remembered serially in terms of i1 and i2 durations, whereas the fast rhythms were coded hierarchically in terms of i1 and i1 + i2.

It is possible that the USAR in classically trained musicians is related to their performance experience with uneven rhythms. As is well known, musicians typically perform rhythms with characteristic deviations from "perfect" timing, in order to give them a particular expressive character (Gabrielsson et al., 1983). As the USAR represents a slight evening out of the 1:2 rhythm, it results in a slightly smoother and more continuous motion. If a musician wanted a melody consisting of successive 1:2 durations (as is often the case in compound meters) to convey a sense of gracefulness or ease, one would expect the deviations characteristic of the USAR. By contrast, if the musician's expressive aim were to project a sense of crisp and emphatic articulation, then one might expect enhanced contrast of interval durations. In both cases the musician would still aim to play the rhythm "correctly," that is, in a consistent manner and congruent with an underlying metrical grid (a grid that itself admits some timing variability—see London, 2012). Although in our experiments there was no musical or aesthetic context and our participants were instructed to perform the rhythms as accurately as possible, there still may have been an unconscious influence of a habitual desire to perform in a fluid and "musical" manner, as fluidity is a highly valued (and much practiced) aspect of expert musical performance. Nonmusician participants, by contrast, may often follow a desire to produce well-contrasted intervals. This explanation, however, applies mainly to the 1:2 rhythm itself: In reproduction of other rhythms, both musicians and nonmusicians show interval assimilation or contrast depending on whether the rhythm has a smaller or larger interval ratio than the hypothetical attractor ratio.

Although the present study and its predecessors examined rhythm production in a simple tapping task, one previous study obtained tendencies towards interval assimilation in production of the 1:2 ratio in a more musical context. Repp, Windsor, and Desain (2002) found this tendency in skilled pianists playing melodies at a "slow" tempo when the metrical accent was on the long note. Their slow tempo had a target cycle duration of 750 ms and thus was similar to the fast tempo in the present study. In another relevant study, Sadakata, Ohgushi, and Desain (2004) had highly trained percussionists perform two-interval rhythms with a drumstick. There was a tendency towards interval assimilation when the metrical accent was on the long note, though it may not have been significant. Neither study found such tendencies when the metrical accent was on the short note. Thus, metrical interpretation seemed to affect rhythm production. In the present study, we did not manipulate metrical interpretation but assumed that the metrical accent was perceived to be on the long note, congruent with the location of the grouping accent (Povel & Okkerman, 1981).

Desain and Honing (2003), in a study of categorization of three-interval rhythms, demonstrated that the center of rhythm categories does not necessarily coincide with the simplest interval ratios. The shape and center of interval categories in the "rhythm space" spanned by the interval durations as dimensions depend both on neighboring categories and on metrical interpretation. Furthermore, Sadakata, Desain, and Honing (2006) formulated a Bayesian theoretical framework in which prior probabilities of different rhythms in music exert an influence on both categorization and rhythm production. What we have called here the attractor ratio (AR) can readily be equated with the center of the 1:2 rhythm category, and the strong categorical tendency observed in production of nearby rhythms reflects the extent of this category. Shifts in the category center away from the simple 1:2 ratio may reflect the relative prior probabilities of this rhythm and of its adjacent rhythm categories. According to estimates derived from music databases, the 1:2 rhythm with metrical accent on the long note is the third-most frequent rhythm after 1:1 and 1:3 (Sadakata et al., 2006). The much higher frequency of the 1:1 ratio may exert an attraction effect on the center of the 1:2 category, thereby causing the USAR. However, we do not know why this effect should differ between musicians and nonmusicians.

It is conceivable that the difference between musicians and nonmusicians lies in different metrical interpretations of the rhythms. If it were the case that musicians tended to hear the 1:2 rhythm as having its metrical accent on the short note, a stronger attraction to the 1:1 category and hence a larger USAR might be predicted because that rhythm is relatively infrequent in music (Sadakata et al., 2006). Such an interpretation, however, seems counterintuitive and contrary to the findings on grouping accent (Povel & Okkerman, 1981). Nevertheless, future studies of the USAR should probably assess or manipulate the metrical interpretation of the rhythms.

One general conclusion we can draw from the present results is that the attractor ratio—the interval ratio of the rhythm that is (or would be) reproduced with perfect accuracy—is not necessarily the mathematically simplest ratio. Even though the observed deviation from 1:2 is small, the fact that there is any consistent shift is problematic for any theory of rhythmic perception and production which privileges simple, low order interval ratios. A special status of such ratios is predicted by all models of rhythmic timing, whether they are nested timekeepers (Pressing, 1998; Vorberg & Hambuch, 1984) or coupled nonlinear oscillators (Large, 2008; Tomic & Janata, 2008). Only recent models of rhythm categorization (Desain & Honing, 2003; Sadakata et al., 2006) allow for deviations of category centers from simple interval ratios. If rhythm reproduction involves prior rhythm categorization, a phenomenon such as the USAR can be explained in principle. However, the results of Experiment 3 suggest that the USAR is not contingent on rhythm categorization and arises directly in musicians' rhythm production. Therefore, an explanation of the USAR remains elusive.

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