Metrical Subdivision Results in Subjective Slowing of the Beat

Bruno H. Repp
Haskins Laboratories

FOUR EXPERIMENTS INVESTIGATED whether metrical subdivision affects perceived beat tempo. In Experiment 1, musically trained participants tapped in synchrony with the beat of an isochronous pacing sequence and continued tapping the beat after the sequence stopped. Continuation tapping was slower when the pacing beat was subdivided than when it was not. Experiment 2 found the same effect when the subdivisions during synchronization were self-generated. The effect was neutralized, however, when subdivisions were tapped during continuation. In Experiment 3, an effect of subdivision was found in a purely perceptual tempo judgment task. Experiment 4 tested musicians and nonmusicians in matched perception and reproduction tasks. Musicians showed the expected effect of subdivision in both tasks, whereas nonmusicians showed a larger effect in reproduction but a smaller effect in perception. Overall, the findings suggest that subdivided inter-beat intervals are subjectively longer than empty intervals, in agreement with the "filled duration illusion" in psychophysics.

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WHEN PEOPLE ARE REQUIRED to tap in synchrony with an isochronous sequence of tones, their taps typically precede the tones by several tens of milliseconds, on average. This is known as the anticipation tendency, negative synchronization error, or *negative mean asynchrony* (NMA). It has given rise to a considerable amount of research but still has not been explained to everyone's satisfaction. (For reviews of some of the explanations that have been proposed, see Aschersleben, 2002, or Repp, 2005.) The NMA decreases as the sequence tempo increases (Mates, Radil, Müller, & Pöppel, 1994; Repp, 2003), and musically trained participants often show only a small NMA (see, e.g., Repp & Doggett, 2007).[1]

One of the explanations proposed for the NMA is of particular interest here. Wohlschläger and Koch (2000) proposed that the NMA is caused by perceptual underestimation of the duration of empty interbeat intervals (IBIs).[2] The timing of taps during synchronization is generally assumed to be governed by an internal timekeeper or oscillator whose period is based on the perceived IBI. If each tap is timed with reference to the previous tone and if the timed interval falls short of the IBI, then each tap will precede the next tone in the sequence. Automatic phase error correction (see Repp, 2005) prevents continuous phase drift and thus ensures a relatively constant NMA. Thus, paradoxically, the taps occur at the correct tempo even though their internal period is too short. This situation is exactly analogous to that of coupled oscillators whose natural frequencies differ slightly, known as "detuning" (see, e.g., Amazeen, Amazeen, & Turvey, 1998): Both oscillators run at the same frequency, but the inherently faster oscillator has a phase lead over the inherently slower one. In human synchronization with an external sequence, the detuning is not due to a natural internal frequency but is assumed to be perceptually induced. Participants presumably do not notice their NMA because their asynchronies are generally below the detection threshold. It is plausible that the absolute

[1]The mean asynchronies reported in that article were near zero. However, Repp and Doggett (2007) did not take into account an electronic processing delay of about 15 ms (*SD* = 1 ms) for sound output and tap registration combined (independent of tapping force), revealed by recent acoustic measurements. Other studies by Repp using the same equipment, published between 2003 and 2007, are subject to the same criticism. The reported asynchronies in all these studies are too long by about 15 ms. Thus, contrary to earlier conclusions (e.g., Repp, 2005), musicians generally do show a NMA, albeit a smaller one than nonmusicians. The 15-ms correction has been applied to the asynchronies in the present study.

[2]The term inter-beat interval (IBI) is used here instead of the more common term inter-onset interval (IOI) to distinguish IBIs (between beats) from IOIs (between successive sounds) once subdivisions of the beat are introduced. The term beat refers here to tones with which taps are to be synchronized in a 1:1 fashion; at the beat rates used here, it is plausible that these tones function as the beat (tactus) in a metrical hierarchy.

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magnitude of IBI underestimation, and thus the NMA, would increase with IBI duration, as it does, and that musicians would be more accurate in their interval perception than nonmusicians and therefore would show a smaller NMA, as they do.

In support of their perceptual underestimation hypothesis, Wohlschläger and Koch (2000) presented two new empirical findings. One was that making extra movements with the finger, or with the toe in a toe-tapping task, during the IBIs reduced the NMA considerably. The proposed reason was that movements give some structure to empty intervals and thereby reduce the underestimation of IBI duration. The other finding was that inserting extra auditory stimuli (soft clicks, sounding like raindrops) randomly into the IBIs had a similar effect. Again, the argument was that the clicks introduce temporal structure and thereby lead to more veridical perception of IBI duration. This claim is consistent with numerous psychoacoustic experiments that have demonstrated an effect known as the *filled duration illusion*: Temporal intervals are perceived as subjectively longer when they are filled with a continuous sound or with one or more discrete sounds than when they are empty (Adams, 1977; Buffardi, 1971; Craig, 1973; Goldfarb & Goldstone, 1963; Hall & Jastrow, 1886; Meumann, 1896; Ornstein, 1969; Thomas & Brown, 1974; Wearden, Norton, Martin, & Montford-Bebb, 2007). This effect has also been demonstrated in the visual and tactile modalities (Buffardi, 1971; Hall & Jastrow, 1886; Israeli, 1930; Roelofs & Zeeman, 1951), and Nakajima (1987) has outlined a theory of empty duration perception that explains it. Most of these studies, however, were concerned with the perception of single intervals. Wohlschläger and Koch (2000), by contrast, were concerned with a rhythmic task that involved both interval perception (implicitly) and interval production. Such a task would seem to be of obvious relevance to music perception and performance, were it not for the randomly timed "raindrops" employed as IBI subdivisions, which are distinctly nonmusical in character.

The main purpose of the present research therefore was to investigate whether the apparent filled duration illusion demonstrated with raindrops in a synchronization task would also occur if the IBIs are subdivided by tones in a metrically regular fashion, as is typically the case in music. Moreover, the research tested whether the effect occurs in musically trained participants who are capable of very accurate temporal perception and production. If it were the case that musicians perceive metrically subdivided beats as slower than simple beats, this might have some interesting implications for tempo perception and tempo choices in performance of music varying in note density.

Several psychophysical studies have already shown that the filled duration illusion is as large or even larger when an interval is subdivided in a temporally regular fashion as when the subdivision is irregular (Buffardi, 1971; Grimm, 1934; Thomas & Brown, 1974). The illusion has also been found to increase with the number of subdivisions. However, these studies were based on perceptual judgments of single intervals, and the intervals were often longer than typical IBIs in music. The effects of subdivision on perceived interval duration were generally larger than could reasonably be expected in a metrical musical context, where precise perception and maintenance of a beat tempo are important. Therefore, it seemed appropriate to investigate whether such subdivision effects are strong enough to persist in metrical contexts and in musically trained participants.

A secondary purpose of the present study, addressed only in Experiment 1, was to further test Wohlschläger and Koch's (2000) perceptual explanation of the NMA in synchronization. If the NMA is due to perceptual underestimation of an empty IBI, and if subdivision of the IBI increases its perceived duration, then the NMA should be reduced by subdivision of the IBI. Wohlschläger and Koch have shown this to be the case with raindrops and musically untrained participants. Can this finding be replicated with metrical subdivision and with musicians as participants? Several specific predictions are considered in the introduction to Experiment 1.

Four experiments were conducted to assess the predicted effect of metrical subdivision in several different ways. The aim of Experiment 1 was to investigate the effect in a synchronization-continuation tapping task, as described in more detail below. Experiment 2 explored several variants of the same paradigm, differing in whether the subdivisions were controlled by the computer or by the participant, in whether or not subdivisions were produced during continuation tapping, and in the presence or absence of enhanced auditory feedback from taps. Experiment 3 examined the effect of metrical subdivision on perceptual judgments of relative tempo. Experiment 4 included matched perception and reproduction tasks, and compared the performance of musicians and nonmusicians.

Experiment 1

The synchronization-continuation tapping paradigm (Stevens, 1886; Wing & Kristofferson, 1973) is a standard method for inducing a particular tempo of self-paced tapping. During synchronization with a regular beat, participants acquire an internal representation of the IBI duration that they then attempt to reproduce with their inter-tap intervals (ITIs) during continuation tapping. In other words, the mean ITI duration during continuation tapping (if it is stable) may provide a direct estimate of the perceived-and-remembered IBI duration. The perceptual underestimation hypothesis of Wohlschläger and Koch (2000) then leads to several specific predictions. First, if a NMA is observed during synchronization and reflects perceptual underestimation of the IBI, the tempo of tapping should accelerate at the transition from synchronization to continuation tapping. This is analogous to the uncoupling of unidirectionally coupled oscillators (one rigid, the other flexible), after which the flexible oscillator's matched period gives way to its natural period. Second, the magnitude of the NMA during synchronization should be positively correlated with continuation ITI duration: The larger the NMA (the larger the perceptual underestimation of the IBI or the "detuning"), the more participants should speed up when continuation tapping starts, and there should be no speeding up when the NMA is zero (i.e., the regression line should pass through the origin). Support for both of these predictions has in fact been found in previous studies by Flach (2005) and also by Repp and Knoblich (2007), whose participants were the same as in the present experiment.[3]

A third prediction concerns the effect of subdivision: Subdividing the IBIs during synchronization should reduce not only the NMA during synchronization but also the speeding up at the start of continuation tapping, because both are assumed to reflect the perceptual underestimation of IBI duration, which is reduced by subdivision. Wohlschläger confirmed the second half of this prediction in an apparently unpublished experiment, reported in a doctoral dissertation he supervised (Caspi, 2002: Figure 5): Adding raindrops during synchronization caused a substantial slowing of the continuation tapping tempo, compared to a baseline condition without raindrops. Curiously, however, participants did not tap faster during continuation than during synchronization in the baseline condition; rather, they maintained the beat tempo quite accurately. Assuming they showed a NMA during synchronization (not reported),

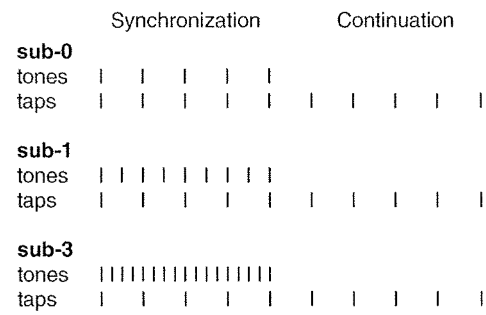

FIGURE 1. Schematic illustration of the sub-0, sub-1, and sub-3 conditions in Experiment 1. (The sub-2 condition is not shown for typographical reasons.) Only the five beats before and after the transition from synchronization to continuation are shown.

this result contradicts the first prediction of the perceptual underestimation hypothesis. Wohlschläger's findings do demonstrate, however, that a filled duration illusion created during synchronization is reflected in the tempo of continuation tapping.

Experiment 1 examined the effect of metrical subdivision during synchronization on the NMA and on continuation ITI duration, and on the correlation between the two. The IBI durations were within a musically appropriate range (cf. Parncutt, 1994). To repeat, the predictions of the perceptual underestimation hypothesis were: (1) The continuation ITI should be shorter than the pacing sequence IBI if there is a NMA during synchronization, (2) NMA and continuation ITI should be affected similarly by subdivision (both should increase) or indeed by any other variable that affects the perception of IBI duration (such as IBI duration itself), and (3) they should be positively correlated within each subdivision condition. Three forms of metrical subdivision common in music (duple, triple, and quadruple) were employed; they are referred to in the following as "sub-n," where n indicates the number of subdivision tones inserted between beats (resulting in n + 1 subdivision intervals). Figure 1 shows a schematic illustration of the sub-0 (baseline), sub-1, and sub-3 tasks. It was expected that the subdivision effect would increase with the number of subdivision tones.

Method

PARTICIPANTS

The participants were seven young paid volunteers (six women) and the author. All were regular participants in synchronization experiments in the author's lab and had extensive music training. Three were graduate students or postgraduates of the Yale School of Music (viola, cello,

[3]Repp and Knoblich (2007) mentioned these findings only in passing (their Footnote 10). Their regression line did not pass exactly through the origin, but their asynchronies also did not include the 15-ms correction mentioned in the present Footnote 1. With that correction, the regression line still misses the origin, however (by –7.5 ms).

bassoon); three were undergraduates, current or former members of the Yale Symphony Orchestra (cello, clarinet, percussion); one was an undergraduate who had had seven years of flute instruction but did not play any more; the author (60 years old at the time) has been an active amateur pianist all his life.

MATERIALS AND EQUIPMENT

Each auditory pacing sequence during synchronization contained 12 beats represented by high-pitched piano tones (A7, MIDI pitch 105, 3520 Hz). Twenty different sequences resulted from the crossing of five IBI durations with four subdivision conditions. The IBI durations were 600, 700, 800, 900, and 1000 ms. The subdivision conditions were sub-0 (baseline), sub-1, sub-2, and sub-3. The subdivision tones were three semitones lower than the beat tones and about 3 dB (10 MIDI velocity units) softer. They started in the third IBI (the first two IBIs were always empty) and divided each IBI into equal IOIs. Each sequence was followed by a long silent interval for continuation tapping whose duration was 10 times the IBI and which was terminated by a single tone, the signal to stop tapping. The 20 sequences were arranged into 10 different random orders (blocks).

The sequences were played back on a Roland RD-250s digital piano under control of a program written in MAX 4.0.9. The software ran on an iMac G4 computer that was connected to the digital piano via a MOTU Fastlane-USB MIDI translator. The tones had no specified offset and decayed freely within about 100 ms.

DESIGN AND PROCEDURE

Participants sat in front of the computer monitor on which the current trial number was displayed, listened to the sequences over Sennheiser HD540 II earphones at a comfortable level, and tapped with the index finger of their preferred hand (the right hand for all but one) on a Roland SPD-6 percussion pad held on their lap. Most participants rested the wrist and other fingers of their hand on the surface of the pad and tapped by moving the index finger only; some, however, also moved the wrist and elbow. The impact of the finger on the rubber pad was audible as a thud, in proportion to the tapping force.

Participants started each sequence by pressing the space bar on the computer keyboard. The sequence started 2 s later. Participants were instructed to start tapping with the third beat, to tap in synchrony with the beats, and to continue tapping the beat at exactly the same tempo after the sequence had ended, until the signal to stop tapping sounded. At the end of each block, participants saved their data and selected the next block. The session lasted about 75 mins.

Results and Discussion

ITI DURATIONS

Figure 2 shows the deviation of ITI duration (averaged across trials within conditions and then across participants) from pacing sequence IBI duration as a function of serial position (abscissa), subdivision condition (legend), and IBI duration (separate panels). The vertical dashed line in each panel marks the end of synchronization and the beginning of continuation tapping. Only the last five synchronization ITIs are shown. The ITIs during synchronization were unaffected by subdivision and very close to the IBIs in all cases. The first continuation ITI (the interval between the last synchronized tap and the first continuation tap, which did not contain any subdivision tones) already showed an effect of (sudden absence of) subdivision; this effect persisted throughout the continuation period. The second continuation ITI was anomalous in that it exhibited a local lengthening, particularly in the baseline (sub-0) condition. Such a local transient at the transition from synchronization to continuation tapping has been observed previously (cf. Repp, 2001, Fig. 2a); it seems to reflect a surprise reaction to the end of the pacing sequence. (When the IBIs were subdivided, the reaction to the cessation of the beat evidently was mitigated by the earlier cessation of the subdivisions.) The first two continuation ITIs were therefore excluded from further analyses, which were based on the seven subsequent ITIs (positions 3-9). As can be seen in Figure 2, the tempo of continuation tapping across these positions was quite stable, on average, except at the slowest tempo (IBI = 1000 ms), where a slight progressive acceleration occurred, irrespective of subdivision.

Figure 3A summarizes the results by showing the mean continuation ITI deviation (now averaged also across serial positions 3-9) as a function of IBI duration (abscissa) and subdivision condition (legend). It is evident, first, that participants were quite accurate in continuing the beat tempo in the baseline (sub-0) condition. Only at the slowest tempo (IBI = 1000 ms) was there a tendency to tap faster during continuation.[4] Second, when the IBIs during synchronization were subdivided

[4]Only one participant (the author) tapped slower, which is partially responsible for the large error bars.

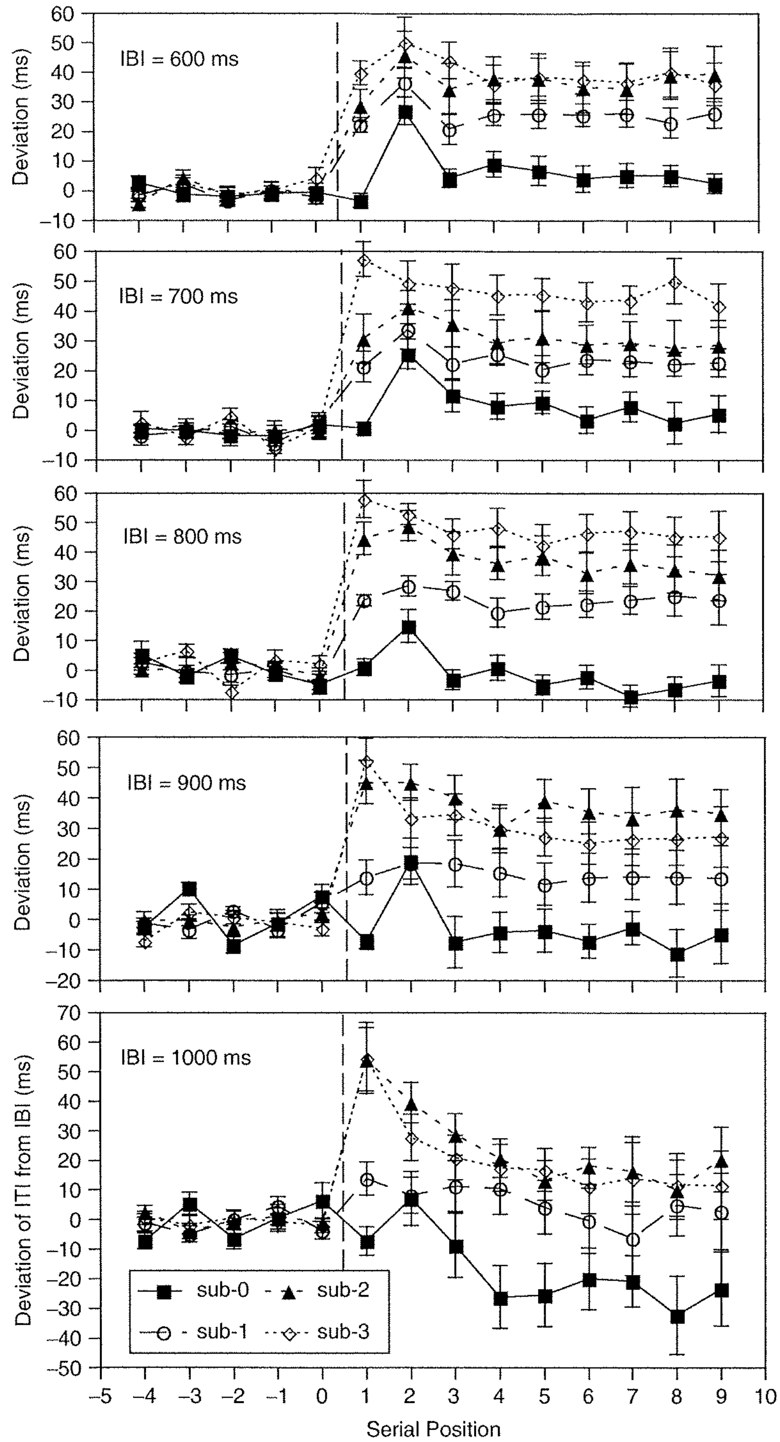

FIGURE 2. Results of Experiment 1: Deviation of mean inter-tap interval (ITI) duration from pacing sequence inter-beat interval (IBI) duration as a function of serial position (abscissa), subdivision condition (legend), and IBI duration (separate panels). The vertical dashed line marks the beginning of continuation tapping. Error bars represent between-participant standard errors.

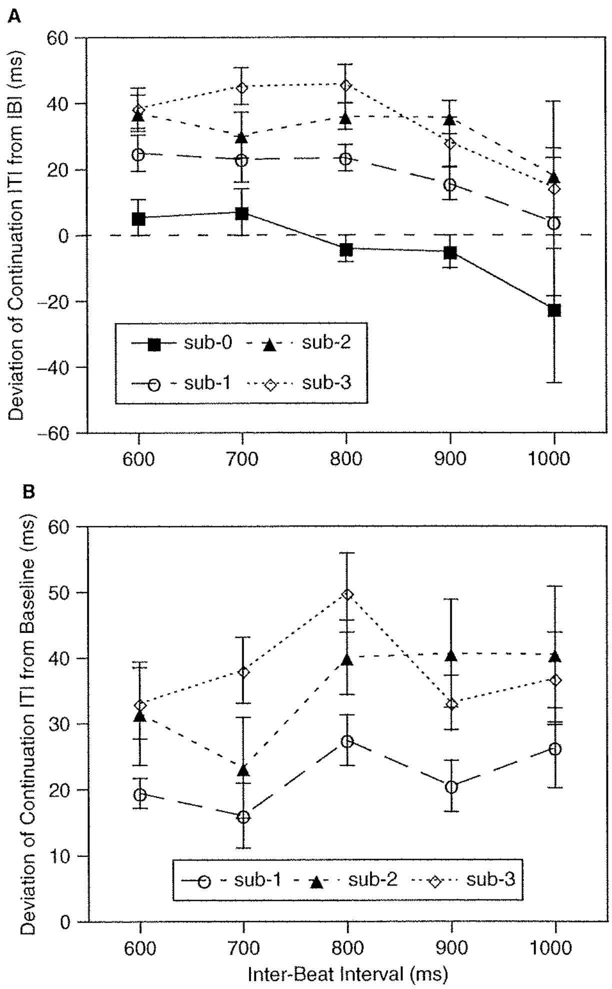

FIGURE 3. Results of Experiment 1: (A) Deviations of mean continuation inter-tap intervals (ITIs) from the pacing sequence inter-beat intervals (IBIs) as a function of IBI duration (abscissa) and subdivision condition (legend). (B) The subdivision effect (difference from the baseline condition in panel A). Error bars represent between-participant standard errors.

(sub-1, sub-2, sub-3), the tempo of continuation tapping was clearly slower than when there was no subdivision. This indicates a filled duration illusion caused by metrical subdivision. The effect also seemed to increase with the number of subdivisions, but only up to sub-2.

A 5 × 4 repeated-measures ANOVA was conducted on these data, with the variables of IBI duration and subdivision condition.[5] The main effect of IBI was significant, $F(4, 28) = 6.67, p < .03$, reflecting the tendency to tap relatively faster (i.e., relative to the IBI) at slow than at fast tempi, especially when IBI = 1000 ms. The main effect of subdivision was highly reliable, $F(3, 21) = 28.21$, $p < .0001$, as it was shown by all participants (including a percussionist!). The IBI × Subdivision interaction did not reach significance, $F(12, 84) = 2.44$, $p < .10$. The main effect of subdivision was due mainly to the difference between the sub-0 condition and the other conditions. However, it was still significant when the sub-0 condition was omitted, $F(2, 14) = 8.41, p < .02$, reflecting the increase between sub-1 and the other two conditions. The sub-2 and sub-3 conditions did not differ significantly, $F(1, 7) = 1.63, p < .25$.

The constancy of the subdivision effect throughout the continuation period was confirmed in an ANOVA on the first and last of the seven analyzed continuation ITIs (serial positions 3 and 9), with position as an additional variable. There was no significant main effect or interaction involving position.

The data are inconclusive as to whether the effect of subdivision was constant across the range of IBIs or whether it was proportional to IBI duration. Figure 3B shows the subdivision effect as the absolute difference between each subdivision condition and the baseline (sub-0) condition in Figure 3A. An ANOVA on these data revealed neither a significant effect of IBI, $F(4, 28) = 2.69, p = .13$, nor an interaction, $F(8, 56) = 2.34, p = .10$, so it could be argued that the subdivision effect was approximately constant across IBI durations. When the subdivision effect was instead expressed as a percentage of IBI duration (or, almost equivalently, of baseline continuation ITI duration), a similar ANOVA yielded slightly larger F values that, however, again did not reach significance, $F(4, 28) = 3.28, p = .09$, and $F(8, 56) = 2.68, p = .07$. Thus, the data do not permit rejection of either the constancy or the proportionality hypothesis, nor are they clearly in favor of one or the other. A constant increment is predicted by Nakajima's (1987) model of duration perception, according to which a sub-1 interval should be subjectively longer than a sub-0 interval by about 80 ms, regardless of interval duration. Clearly, the present sub-1 effect was much smaller than predicted by Nakajima's model, which was intended to explain the perception of single intervals, not the behavior of musicians tracking a beat. Moreover, Nakajima's model also predicts equal increments in subjective duration for each additional subdivision, which was not evident in the present data. Rather, the subdivision effect seemed to reach its maximum with two subdivision tones.

The within-trial standard deviation of the continuation ITIs (not shown in Figure 3) clearly increased with

[5]All F values with more than one degree of freedom in the numerator were subjected to the Greenhouse-Geisser correction.

IBI (and mean ITI) duration, $F(4, 28) = 38.81$, $p < .0001$, which is a ubiquitous finding (e.g., Madison, 2001; Peters, 1989). The increase was quite linear, $F(1, 7) = 79.62$, $p < .0001$, and the mean coefficient of variation was 3% or less. Subdivision during synchronization did not have a significant effect on variability of continuation tapping.

ASYNCHRONIES

We now turn to the asynchronies during synchronization, which according to the perceptual underestimation hypothesis should be closely related to the continuation ITIs. The first three asynchronies were omitted from analysis, and means and standard deviations were calculated for the remaining seven asynchronies in each trial. The mean asynchronies, shown in Figure 4A, were negative but relatively small, as had been expected for musically trained participants. They decreased systematically as IBI duration increased, $F(4, 28) = 25.39$, $p < .0001$; only the linear component of the decrease was significant, $F(1, 7) = 27.78$, $p < .001$. Similar trends have been observed in previous studies (e.g., Mates et al., 1994; Repp, 2003). The decrease parallels (if only roughly) the decrease in ITI deviations as IBI duration increased (Figure 3A). In stark contrast to the continuation ITIs, however, the asynchronies were barely affected by subdivision of the IBIs. Although the main effect of subdivision reached significance, $F(3, 21) = 3.98$, $p < .04$, it was quite small and seemed to be due solely to the sub-2 condition. This result is inconsistent with the third prediction of the perceptual underestimation hypothesis.

Moreover, the asynchronies in all conditions were negative, which according to the perceptual underestimation hypothesis should lead to speeding up during continuation tapping in all conditions. Such speeding up, however, did not occur in any of the subdivision conditions, and in the baseline condition it occurred to a much smaller extent than would be predicted from the asynchronies. The results, therefore, are also inconsistent with the first prediction of the perceptual underestimation hypothesis.

The second prediction of the perceptual underestimation hypothesis is that the NMA during synchronization and the mean ITI during continuation tapping should be positively correlated (across participants): The larger the NMA, the faster the continuation tapping should be. Recall that Repp and Knoblich (2007) found such a correlation for the same participants as were tested here, in a study that did not involve subdivision. Here the correlation was assessed within each subdivision condition after averaging each participant's

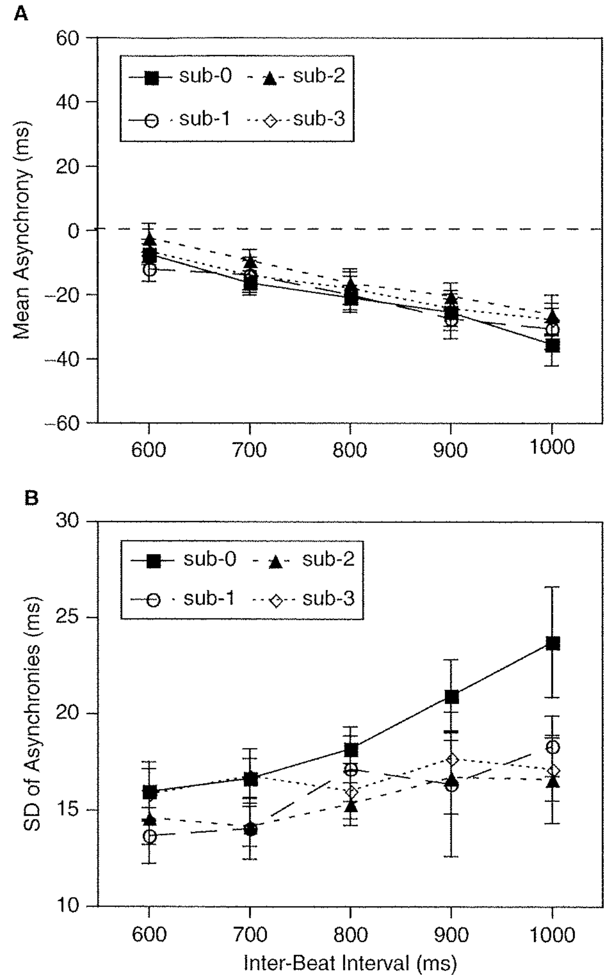

FIGURE 4. Results of Experiment 1: (A) Mean asynchronies and (B) mean within-trial standard deviations of asynchronies during synchronization as a function of inter-beat interval duration and subdivision condition. Error bars represent between-participant standard errors.

data across the five IBI conditions, to increase the stability of individual data.[6] Within the sub-0 condition there was indeed a positive correlation that approached significance, $r(6) = .64$, $p < .10$, comparable to the correlation obtained by Repp and Knoblich. Thus, participants

[6]The correlations were also computed separately for each combination of IBI duration and subdivision condition. This revealed that the positive correlations in the sub-0 and sub-1 conditions derived mainly from the two longest IBIs. Furthermore, correlations between mean asynchrony and mean continuation ITI were computed across trials within each of the twenty conditions, separately for each participant. These 160 correlations were subjected to a repeated-measures ANOVA which revealed no significant effect of either IBI duration or subdivision condition. The grand mean across-trial correlation was .21, which is significantly different from zero, $t(19) = 5.89$, $p < .001$, but accounts for less than 5% of the variance.

who showed a larger (more negative) NMA overall did tend to tap faster during the continuation period than those who showed a smaller NMA. The correlation in the sub-1 condition was likewise positive, $r(6) = .50$, but the correlations in the sub-2 and sub-3 conditions were slightly negative, $r(6) = -0.26$, and -0.10, respectively, all nonsignificant. The absence of correlations in these conditions could be explained by noting that the timing of on-beat taps is guided not only by preceding beats but also by preceding subdivision tones (Large, Fink, & Kelso, 2002; Repp, 2003, 2008). Thus, the presence of shorter intervals created by subdivisions may have made an internal representation of the IBI irrelevant to the mean asynchronies. This argument might also explain why subdivision had so little effect on mean asynchronies. However, the argument is not part of the perceptual underestimation hypothesis, which would have to be modified to include it.

For good measure, Figure 4B shows the standard deviations of the asynchronies. Although they are not directly relevant to the issues addressed here, they are relevant to earlier findings concerning a "subdivision benefit" during synchronization. Repp (2003) found that the variability of asynchronies was reduced by explicit subdivision of IBIs, as long as the subdivision intervals exceeded 200 ms. Here, apart from the expected general increase in variability with IBI (and ITI) duration, $F(4, 28) = 18.12, p < .0001$, variability was indeed reduced by subdivision, $F(3, 21) = 16.0, p < .0001$, and increased less with IBI duration when subdivisions were present, as reflected in a significant interaction, $F(12, 84) = 3.49$, $p < .02$. Only two specific combinations of subdivision and IBI duration did not yield a benefit; these were the sub-3 conditions with IBIs of 600 and 700 ms, in which the durations of the subdivision intervals were 150 ms and 175 ms, respectively.[7] Two combinations with subdivision intervals of 200 ms (sub-3 with IBI = 800 ms and sub-2 with IBI = 600 ms) still seemed to yield a benefit here, perhaps because the participants had more music training than the previous participants. On the whole, these results are quite consistent with the previous findings and replicate the subdivision benefit.

CONCLUSIONS

The results of Experiment 1 demonstrate that metrical subdivision results in a subjective slowing of the beat: When continuing to tap the beat, participants tapped slower following a subdivided beat sequence than following a simple beat sequence. This subdivision effect replicates Wohlschläger's "raindrop" findings (reported by Caspi, 2002) and generalizes them to metrical subdivisions and to musically trained participants. Like raindrops, but in a more musically relevant way, regular subdivisions fill the empty IBIs and structure them, and this apparently increases the subjective duration of the IBIs. That is, the subdivisions give rise to a filled duration illusion (Buffardi, 1971; Grimm, 1934; Thomas & Brown, 1974) that, while smaller than in most psychophysical single-interval studies, is strong enough to overcome musicians' acute temporal sensitivity and their highly trained ability to maintain a steady beat.

The results of Experiment 1 offer but little support for the perceptual underestimation explanation of the NMA (Wohlschläger & Koch, 2000). While there is no reason to doubt that the tempo of continuation tapping reflects an internal representation of a previously perceived beat tempo, it is less clear whether the timing of taps during synchronization is governed by the same internal representation. Although an internal timekeeper or oscillator is clearly needed for synchronization, perhaps this mechanism is not identical with the timekeeper or oscillator employed during continuation tapping. The timer employed during synchronization may be more passive and less involved in conscious perception than the active and perceptually informed mechanism used during self-paced tapping. This very speculative hypothesis warrants further investigation. Alternatively, if the same timing mechanism is involved in synchronization and continuation tapping, then the present data suggest that there are other variables that also influence the NMA (see Aschersleben, 2002; Repp, 2005). Unlike the continuation ITIs, the NMA does not appear to be a direct measure of IBI perception.

The following experiments deal no longer with the NMA during synchronization but focus exclusively on the subdivision effect.

Experiment 2

Experiment 2 explored four variants of the synchronization-continuation tapping paradigm with subdivision. Two variants were inspired by Wohlschläger's unpublished experiment (Caspi, 2002). In that study, Wohlschläger added raindrops not only during synchronization but also during continuation tapping or during both of these trial phases. The addition of raindrops during continuation tapping alone had little effect, but the effect of raindrops during synchronization on the tempo of continuation tapping (the subdivision effect)

[7] Only the single percussionist among the participants still showed a benefit in those conditions, which probably reflects her superior rhythmic skill.

was reduced substantially when raindrops were added during continuation tapping as well. Presumably, this occurred because subdivided ITIs during continuation tapping were perceived as longer and thus approximated the perceived duration of the subdivided IBIs. One reason why there was still a residual subdivision effect, and why raindrops during continuation tapping alone had no effect at all, may be the fact that the continuation taps were not accompanied by tones. Thus there was a perceptual dissimilarity between the pacing sequence during synchronization and the perceptual feedback during continuation tapping; also, the raindrops may not have been very effective subdividers of ITIs marked mainly by tactile and proprioceptive cues.

Two conditions of Experiment 2 therefore investigated whether the metrical subdivision effect can be reduced or canceled by metrical subdivision during continuation tapping. Because computer-controlled metrical subdivision of ITIs (unlike random raindrops) would effectively pace continuation tapping, the participants themselves were required to produce the subdivisions with their left hand. A condition without special auditory feedback (although the taps could be heard as soft thuds) was compared with one in which all continuation taps produced tones identical to those of the pacing sequence during synchronization (cf. Flach, 2005; Repp & Knoblich, 2007). It was expected that reduction of the subdivision effect would be more effective in the second condition than in the first; in fact, complete cancellation of the effect was predicted in that condition.

Since self-generated subdivisions were used during continuation tapping in the first two conditions, two other conditions of Experiment 2 explored whether self-generated metrical subdivisions during synchronization would generate a subdivision effect similar to that exerted by computer-controlled metrical subdivisions. Again, two feedback conditions were compared: one in which the subdivision taps (made with the left hand) did not produce tones (only thuds), and another one in which the taps triggered subdivision tones. It was expected that the first condition might give rise to a weak subdivision effect, whereas the second condition would exhibit a full-fledged effect. Although self-generated subdivisions differ from computer-generated ones in that they have some timing variability, this was not expected to have much influence on the subdivision effect.

As a fifth condition, Experiment 2 included a replication of the basic subdivision effect (i.e., with computer-controlled subdivisions during synchronization), to make sure the participants (the same as in Experiment 1) still showed the effect, and to have a baseline for Experiment 2.

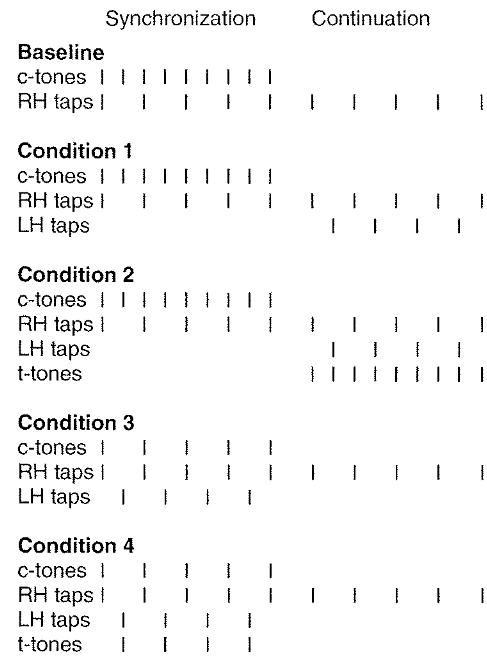

FIGURE 5. Schematic illustration of the conditions in Experiment 2, for simple subdivision (sub-1). Only the five beats before and after the transition from synchronization to continuation are shown. RH = right hand; LH = left hand; c-tones = computer-controlled tones; t-tones = tap-controlled tones.

To reduce the length of the experiment, only three sequence tempi and three subdivision conditions were employed in all conditions. Because the tapping of fast subdivisions with the left hand might have been difficult, the two faster tempi of Experiment 1 and the sub-3 condition were omitted. A schematic illustration of the five experimental conditions for the sub-1 condition is shown in Figure 5.

Method

PARTICIPANTS

The participants were the same as in Experiment 1. About three months had elapsed, during which all participants had performed in various other synchronization experiments.

MATERIALS AND EQUIPMENT

The pacing sequence IBIs were 800, 900, and 1000 ms. The subdivision conditions were sub-0, sub-1, and sub-2. This resulted in 9 different sequences that were presented in 10 different random orders (blocks) in each of the five experimental conditions.

The computer-controlled pacing sequences in the baseline condition and in Conditions 1 and 2 were identical with the ones used in Experiment 1. The pacing sequences in Conditions 3 and 4, where participants had to produce subdivisions during synchronization, had two new features: First, in the sub-1 and sub-2 conditions subdivision tones were present during the first two IBIs, serving as a cue telling participants how to subdivide the subsequent IBIs. Second, in all sequences the last two beat tones were lower than the preceding beat tones by 3 and 5 semitones, respectively, which cued participants to stop subdividing in the sub-1 and sub-2 conditions.

In the baseline condition and in Conditions 1 and 3, taps did not produce tones.[8] In Condition 2, all continuation taps triggered feedback tones identical with the tones of the pacing sequence, with subdivision tones differing from beat tones, as in Experiment 1. In Condition 4, only the left-hand subdivision taps during synchronization (but not the right-hand taps, which were synchronized with the computer-controlled beat tones) produced tones. There was an electronic processing delay of about 15 ms between each tap and its feedback tone (see Footnote 1). The equipment was the same as in Experiment 1.

PROCEDURE

Each numbered condition (1-4) constituted a separate session. Sessions were usually at least one week apart. Two or three blocks of the baseline condition were presented at the end of each session. The order of the sessions was counterbalanced across participants. A few practice trials were given at the beginning of each session. Each session lasted about 50 mins.

The procedure was the same as in Experiment 1, except for the following differences. Participants tapped beats with their right hand and subdivisions with their left hand, using different sub-pads of the SPD-6 electronic percussion pad.[9] In Conditions 1 and 2, participants were instructed to tap with the beats of the pacing sequence until it stopped and then to continue tapping the beats with their right hand and the subdivisions (if any) with the left hand. The ITI between the last synchronization tap and the first continuation tap remained empty because participants had to detect that the sequence had ended before they could start tapping the subdivisions. In Conditions 3 and 4, participants were instructed to tap in synchrony with the beats of the pacing sequence with their right hand while continuing any subdivisions heard during the first two IBIs of the pacing sequence by tapping with their left hand, starting in the third IBI. After the end of the pacing sequence, which was announced by two successive shifts of the beat tones to a lower pitch, participants were to discontinue tapping subdivisions and just to continue tapping the beat with their right hand. The importance of maintaining the beat tempo precisely was stressed in all conditions.

Results and Discussion

The analysis focused on the beat ITIs during continuation tapping. Figure 6 shows the deviations of the mean continuation ITIs from the IBIs in the baseline condition and in the four experimental conditions (separate panels). These analyses are based on eight ITIs per trial, starting with the one between the second and third continuation taps.

BASELINE CONDITION

The results for the baseline condition replicate closely the corresponding Experiment 1 data (Figure 3A). Thus, the subdivision effect persisted even though the participants were no longer naïve, which confirms its perceptual basis. Clearly, it is an effect of which participants are quite unaware. A 3 × 3 repeated-measures ANOVA showed a robust main effect of subdivision, $F(2, 14) = 25.55, p < .001$. Although there was a downward trend in the deviations as a function of IBI duration, just as in Experiment 1, the main effect of IBI duration was not significant, $F(2, 14) = 2.74, p < .12$, nor was the interaction. As in Experiment 1, the subdivision effect tended to be larger for sub-2 than for sub-1, but that difference also failed to reach significance here, $F(1, 7) = 4.40, p < .08$.

CONDITIONS 1 AND 2

Condition 1, in which participants continued to tap both beats and subdivisions, but without generating tones, was expected to show a reduced subdivision effect. Indeed, in the ANOVA on these data the main effect of subdivision did not reach significance, $F(2, 14) = 2.77, p < .10$, although there was a difference between the sub-1 and sub-2 conditions similar in magnitude to that in the baseline condition. The main effect of IBI duration (a tendency to tap relatively faster at slower tempi) reached

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[8] In hindsight, it might have been useful to include a baseline condition with feedback tones during continuation tapping, to make the design complete.

[9] Two participants were left-handed but had no difficulty with this hand assignment. One of them had tapped with the right hand in Experiment 1.

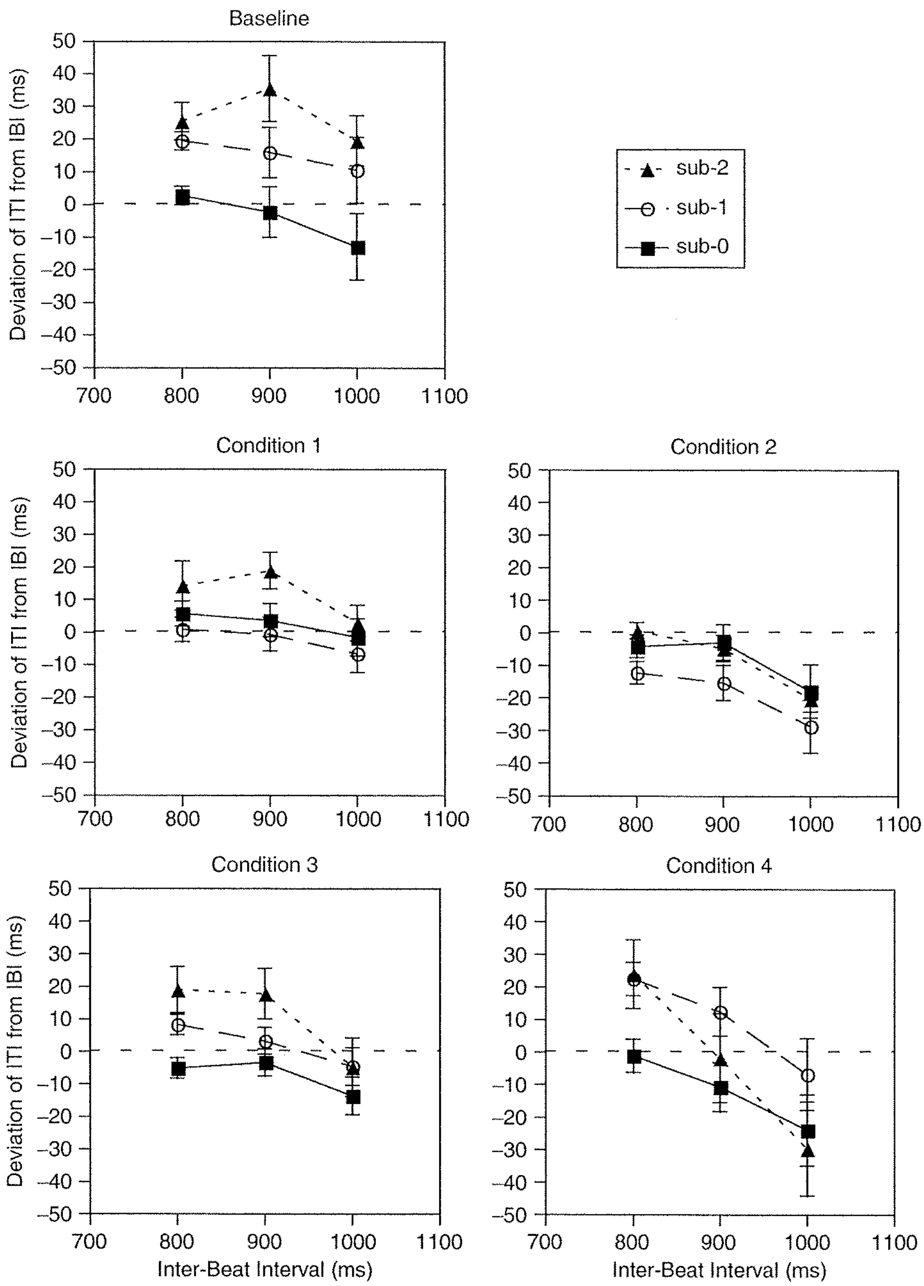

FIGURE 6. Results of Experiment 2: Deviations of mean continuation inter-tap intervals (ITIs) from the preceding inter-beat intervals (IBIs) as a function of IBI duration and subdivision condition in the baseline condition and in the four experimental conditions. Error bars represent between-participant standard errors.

significance here, $F(2, 14) = 5.36, p < .03$. The interaction was not significant. A joint ANOVA was conducted on the data from this condition and the baseline condition, with the additional variable of condition. In addition to significant main effects of subdivision, $F(2, 14) = 15.65$, $p < .001$, and IBI duration, $F(2, 14) = 4.54, p < .05$, there was a significant Condition × Subdivision interaction, $F(2, 14) = 5.86, p < .02$, which confirmed that the subdivision effect (if any) in Condition 1 was reliably smaller than in the baseline condition.

The subdivision effect was predicted to disappear entirely in Condition 2, where tones accompanied the continuation taps. Indeed, the main effect of subdivision was not significant, $F(2, 14) = 2.32$, $p < .15$, although unexpectedly there seemed to be still a difference between the sub-1 and sub-2 conditions. Participants also tapped faster overall than in Condition 1, and there was a more pronounced downward trend as a function of IBI duration, $F(2, 14) = 11.09$, $p < .004$. In a joint ANOVA of Conditions 1 and 2, there was a significant main effect of IBI duration, $F(2, 14) = 9.77$, $p < .006$, a significant main effect of condition, $F(1, 7) = 12.21$, $p < .01$, and a significant Condition × IBI interaction, $F(2, 14) = 4.37$, $p < .05$, but no significant effect involving subdivision. Still, the main effect of subdivision hovered close to significance, $F(2, 14) = 3.33$, $p = .08$, evidently due to the persisting difference between the sub-1 and sub-2 conditions. When Condition 2 was compared with the baseline condition in a joint ANOVA, both the main effect of Condition, $F(1, 7) = 14.45$, $p < .007$, and the Condition × Subdivision interaction, $F(2, 14) = 20.67$, $p < .001$, were significant, in addition to the expected main effects of subdivision and IBI duration. The Condition × IBI interaction was not significant.

Thus, tapping subdivisions during continuation indeed reduced or eliminated the subdivision effect, as predicted. The residual difference between the sub-1 and sub-2 conditions is puzzling, however, and remains unexplained for the time being.[10] The tendency to accelerate continuation tapping in Condition 2 may be attributed to the 15-ms delay between taps and feedback tones. Flach (2005) has shown that the tempo of continuation tapping varies systematically with the delay between taps and feedback tones: When the delay is shorter than the NMA, people tend to accelerate; when it is longer than the NMA, people tend to slow down. This can be interpreted as a tendency to maintain the temporal relationship between taps and tones from synchronization to continuation. If the NMAs (not analyzed here) were similar to those in Experiment 1, roughly between -20 and -30 ms (see Figure 4A), the relative speeding up in Condition 2 is consistent with Flach's observations.

CONDITIONS 3 AND 4

In Condition 3, participants tapped subdivisions during synchronization but did not hear any subdivision tones. The question was whether this would give rise to a subdivision effect. The data in Figure 6 do suggest an effect, but it was smaller than in the baseline condition and fell short of significance, $F(2, 14) = 3.44$, $p < .07$. There was a significant downward trend as a function of IBI duration, $F(2, 14) = 7.21$, $p < .03$. In a joint ANOVA with the baseline condition, the main effect of subdivision was significant, $F(2, 14) = 11.66$, $p < .02$, but the Condition × Subdivision interaction fell short of significance, $F(2, 14) = 3.20$, $p < .08$. Thus, although the subdivision effect in Condition 3 was not quite reliable by itself, it was also not reliably smaller than the effect in the baseline condition.

Finally, in Condition 4 participants heard tones when they produced the subdivisions during synchronization, and this was expected to give rise to a subdivision effect similar to that in the baseline condition. Here the results took a surprising turn in the form of grossly deviant results for sub-2, which showed a steep decrease as IBI duration increased, so that the sub-2 subdivision effect vanished at the longer IBIs. The results for sub-0 and sub-1, however, were indeed similar to those in the baseline condition. An ANOVA on Condition 4 revealed a marginally significant main effect of subdivision, $F(2, 14) = 3.84$, $p < .05$, but a strong main effect of IBI duration, $F(2, 14) = 17.86$, $p < .003$, and a significant interaction, $F(4, 28) = 5.85$, $p < .02$. In a joint ANOVA with Condition 3, the main effect of subdivision was not quite significant, $F(2, 14) = 3.72$, $p < .06$, but the main effect of IBI duration was strong, $F(2, 14) = 14.36$, $p < .004$, and there was a significant Condition × IBI interaction, $F(2, 14) = 12.82$, $p < .005$, confirming that the effect of IBI duration was stronger in Condition 4 than in Condition 3. The main effect of condition was not significant. A joint ANOVA of Condition 4 with the baseline condition showed a number of significant differences including a significant triple interaction, $F(4, 28) = 6.98$, $p < .007$. To confirm that this interaction was due to the wayward pattern of the sub-2 condition data in Condition 4, the ANOVA was repeated with either the sub-2 or the sub-1 condition omitted. Without the sub-2 condition, there was no significant interaction, indicating that the subdivision effect was equally large in the baseline condition and in Condition 4. Without the sub-1 condition, the Condition × Subdivision interaction was significant, $F(1, 7) = 9.32$, $p < .02$, as were the Condition × IBI interaction, $F(2, 14) = 29.85$, $p < .001$, and the triple interaction, $F(2, 14) = 7.51$, $p < .02$.

It is curious that the anomalous speeding up in the sub-2 condition occurred at the slowest beat tempo. This makes it unlikely that it reflects a motor problem. Inspection of individual data revealed that the effect

[10] In a combined ANOVA on the baseline condition and Conditions 1 and 2, the difference reached significance, $F(1, 7) = 7.18$, $p < .04$, and did not interact with condition.

was not due to acceleration during continuation tapping (although there was a small tendency in that direction, as in Experiment 1). However, there were large individual differences, and the anomalous pattern was shown only by some participants (probably those with weaker rhythmic skills, as they included the author and the inactive flutist, but not the percussionist). Its exact cause remains unexplained for the time being.

CONCLUSIONS

Despite some unexpected aspects of the results, Experiment 2 basically confirmed the predictions made at the outset. First, the basic subdivision effect was replicated. Second, continuation tapping that included subdivision taps largely eliminated the subdivision effect because it made the synchronization and continuation phases perceptually more similar, especially when the taps triggered tones. Third, self-generated subdivisions during synchronization led to a subdivision effect, at least in the case of simple subdivision (sub-1), and more effectively so when the subdivision taps were accompanied by tones. Thus, it is not necessary for subdivision to be computer-controlled; the feeling of agency seems to be irrelevant to the subdivision effect and to continuation tapping more generally (see Flach, 2005; Repp & Knoblich, 2007).

Experiment 3

The purpose of Experiment 3 was to investigate the metrical subdivision effect in a purely perceptual task, requiring comparative tempo judgment. If a subdivided IBI seems longer than an empty IBI, then listeners should judge a subdivided beat sequence to be slower than a simple beat sequence when both have the same tempo. To be judged as having the same tempo as the simple beat sequence, the subdivided sequence would have to be faster.

Caspi (2002) conducted such a perceptual study with sequences containing raindrops. A standard sequence consisting of eight isochronous beats was followed immediately by a comparison sequence consisting of five isochronous beats. The IBI of the standard sequence was fixed at 800 ms, whereas that of the comparison sequence was either the same or differed by ±5% or ±10%. Raindrops were either present or absent during the standard sequence. Participants had to report whether the sequence accelerated or decelerated towards the end, making a forced choice. Their responses indicated that, when raindrops were present during the standard sequence, the comparison sequence was judged to be at the same tempo as the standard sequence when it was in fact slower by about 3% (~24 ms). The present experiment used a similar task to assess the perceptual magnitude of the metrical subdivision effect.

Method

PARTICIPANTS

Eight paid participants were recruited from among Yale students; in addition, a research assistant and the author participated. There was a wider range of musical experience in this group than in that of Experiments 1 and 2. Four participants had extensive music training (10 years or more), whereas three had only limited training (2-3 years). For the remaining three participants musical background information was not recorded.

MATERIALS AND EQUIPMENT

The sequences employed were shorter than those of Caspi (2002), consisting of only seven beat tones. The first three IBIs were considered the standard sequence and the last three IBIs the comparison sequence. The standard IBIs were either empty (sub-0) or subdivided metrically by one, two, or five additional tones (sub-1, sub-2, sub-5).[11] The beat and subdivision tones were the same as in Experiments 1 and 2. The standard IBI duration was fixed at 600 ms. Comparison IBIs had one of seven durations, ranging from 528 ms (–12%) to 672 ms (+12%) in steps of 24 ms (4%). This resulted in 28 different sequences that were presented in ten different random orders (blocks). The equipment was the same as in Experiments 1 and 2.

PROCEDURE

Participants were requested to judge whether they perceived a tempo change in the beat halfway through a sequence, and if so, whether the change was an acceleration or a deceleration. Thus, in contrast to Caspi's (2002) study, "same" ("no change") responses were permitted, which seems more natural than having to make a forced choice between two alternatives neither of which corresponds to the actual percept. The responses were given using the three arrow keys in the bottom row of the computer keyboard, which were labeled for that purpose. A block of trials was started by a mouse click on the screen; subsequently each response triggered the next trial after a 2-s delay. There was a brief

[11]The sub-5 condition was really intended to be a sub-3 condition. The mistake during stimulus preparation was not noticed until much later; fast subdivisions with 150-ms and 100-ms IOIs do not sound strikingly different.

pause after each block during which the data were saved. The duration of the session was about 45 mins.

Results and Discussion

Figure 7 shows the mean response percentages in the four subdivision conditions as a function of the relative change in IBI duration between the standard and comparison sequences. In the sub-0 condition a change of about ±6% was required for a tempo change to be detected 50% of the time. Looking across the panels, it can be seen that the distribution of "same" responses shifted towards the slow side as the number of subdivision tones increased, which is the predicted direction. The effect was asymmetric, being due mainly to a decrease in "slower" responses.

An estimate of the subjective point of equality (SPE) was calculated separately for each participant in each subdivision condition. The SPE was computed as the weighted mean of the seven IBI changes, with the "same" response percentages as weights. The mean SPEs are shown in Figure 8. The upper panel shows the results for all ten participants, whereas the lower panel shows the results after exclusion of two participants who tended to show a negative subdivision effect. They happened to be the author and his research assistant. It could be argued that their knowledge of the effect to be tested led them to compensate for it subconsciously. The author, however, had shown a robust subdivision effect in Experiments 1 and 2; thus it may be that the subdivision effect is more fragile in perception than in production. This is also suggested by the fact that a single

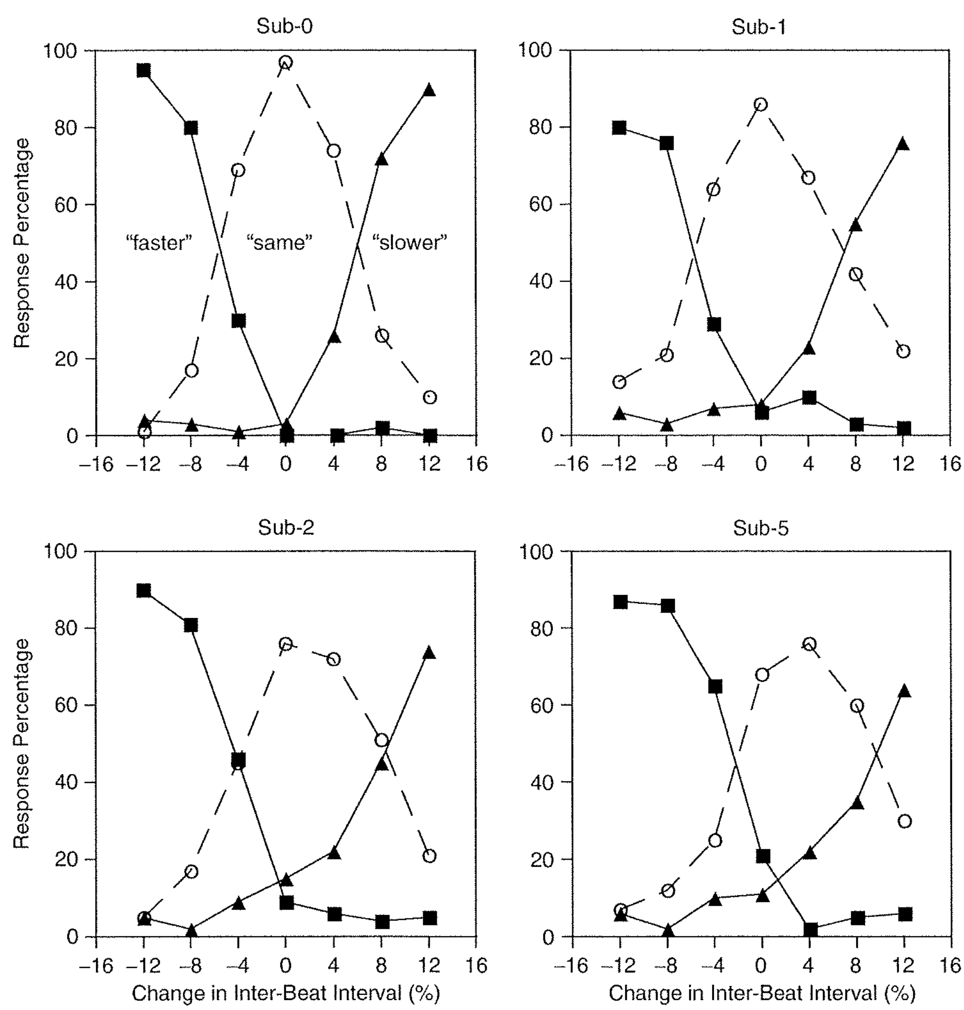

FIGURE 7. Results of Experiment 3: Response percentages in the four subdivision conditions as a function of the change in IBI duration between the standard and comparison sequences.

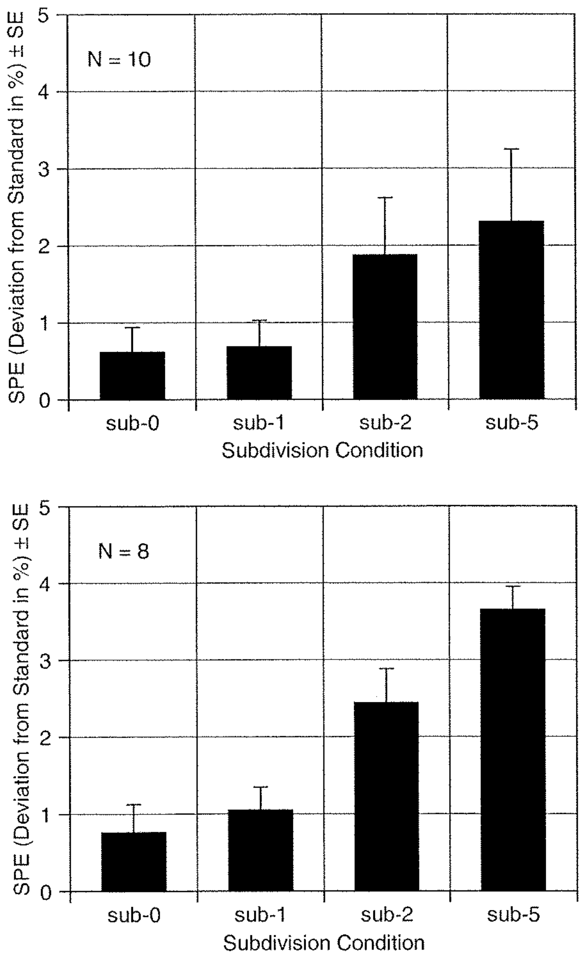

FIGURE 8. Deviations of points of subjective equality (SPEs) from the target IBI (600 ms), derived from the "same" responses in Figure 7. Results are shown for all ten participants (upper panel) and with two non-naïve participants excluded (lower panel). Error bars represent between-participants standard errors.

subdivision (sub-1) was ineffective. The sub-2 and sub-5 conditions, however, did show the predicted effect.

With all participants included, the effect of subdivision on the SPE did not reach significance, $F(3, 27) = 2.99$, $p < .09$; after the two deviant participants were excluded, however, the effect was highly reliable because all remaining participants showed it, $F(3, 21) = 30.29$, $p < .001$. The effect was slightly larger in the sub-5 than in the sub-2 condition, $F(1, 7) = 7.53$, $p < .03$. The mean effect in these two conditions is about 3% (~18 ms). The percentage is in agreement with Caspi's (2002) raindrop findings; the absolute value is a bit smaller here. The sub-2 effect at IBI = 600 ms in Experiment 1 was about twice as large as the present effect (see Figure 3A). There was also a robust sub-1 effect in continuation tapping, but not here in perception. It thus appears that the subdivision effect is smaller in perception than in production. There are various differences in the paradigms, however, that could be responsible for the different effect sizes. An attempt to equate them, as much as possible, was made in Experiment 4.

Experiment 4

Experiment 4 tested perception and production in the same participants, focusing on the sub-3 condition (which had inadvertently been omitted from Experiment 3). Testing the same participants in similar paradigms made it possible to compare the subdivision effects in the two tasks. Furthermore, Experiment 4 included both musically trained and untrained participants, in order to see whether they would show different effect sizes. (In Experiment 3, there was not sufficient information about participants' musical background to make a systematic comparison.)

Some changes were made in the materials to make the two tasks more similar, and some other changes were made for the sake of generality. In the perception task, a silent interval amounting to one skipped beat was inserted between the standard and comparison sequences, which were also made somewhat longer than those in Experiment 3. Instead of a synchronization-continuation tapping task, a reproduction task was used: After listening to a short target sequence without tapping along, participants had to reproduce the beats of that sequence by means of tapping, trying to match the target beat tempo as precisely as possible. The perception and reproduction tasks were matched in terms of sequence length and range of IBIs. The pitches of the beat and subdivision tones were also the same in the two tasks, but different from previous experiments.

Method

PARTICIPANTS

Thirteen Yale undergraduates were paid to participate, and in addition the author and his research assistant completed the tasks. Eight of the 15 participants, referred to as musicians, had substantial music training (7 years or more), whereas of the other seven, referred to collectively as nonmusicians, two had little training (1-2 years) and five had none at all.

MATERIALS AND EQUIPMENT

In the perception task, the standard IBI duration was again 600 ms. Each standard sequence consisted of five isochronous beat tones, either without subdivisions (sub-0) or with three metrical subdivision tones intervening between beats (sub-3). After a silent interval of 1200 ms, a comparison sequence followed, consisting of five isochronous beat tones without subdivisions. Across trials, the IBI duration of the comparison sequence varied from 528 ms (−12%) to 672 ms (+12%) in steps of 24 ms (4%), as in Experiment 3. This resulted in 14 different trials, which were presented in 8 (for some participants, 10) different randomizations (blocks).

In the reproduction task, each trial presented a target sequence consisting of five isochronous beat tones, without (sub-0) or with (sub-3) metrical subdivisions, at one of seven IBI durations, ranging from 528 to 672 ms in steps of 24 ms. Thus, the range of target IBIs was equal to the range of comparison IBIs in the perception task. The resulting 14 trials were presented in 8 (for some participants, 10) different randomizations (blocks).

The beat tones had a lower pitch than in previous experiments (E6, MIDI pitch 80, 1319 Hz), and the subdivision tones were just one semitone lower (1245 Hz) but still about 3 dB (10 MIDI velocity units) softer. Their nominal duration was 40 ms. The equipment was the same as in previous experiments.

PROCEDURE

Roughly half the participants did the perception task before the reproduction task; for the others, the order was reversed. Both tasks were completed in a single session of about 60 mins. The perception task proceeded as in Experiment 3. In the reproduction task, each trial was initiated by pressing the space bar on the computer keyboard; the target sequence started 2 s later. Participants were instructed to reproduce the beat tones of the target sequence at the exact tempo by tapping on the SPD-6 electronic percussion pad and to ignore any subdivisions. Each tap triggered a beat tone of constant intensity and duration, so that the reproduction task was perceptually similar to the perception task. Musicians were told to leave an interval corresponding to one silent beat between the target sequence and their reproduction. Nonmusicians were merely told to leave a brief pause.

Results and Discussion

PERCEPTION TASK

The results of the perception task are shown in Figure 9. The upper panels show the percentages of "same" responses in the two subdivision conditions, separately for musicians and nonmusicians. (The percentages of "faster" and "slower" responses are omitted to avoid clutter.) The lower panels show the corresponding mean SPEs as percentage deviations from the target IBI. The group of musicians showed a clear subdivision effect, $F(1, 7) = 22.7, p = .002$. All participants (including the author, who had not shown an effect in Experiment 3) showed the effect, and the mean effect (about 3%) was similar in magnitude to that obtained in the sub-2 and sub-5 conditions in Experiment 3. The nonmusicians were much less accurate in their judgments, especially when subdivisions were present, and although they showed a similar shift in their "same" responses, their mean SPEs in the sub-0 and sub-3 conditions were not significantly different, $F(1, 6) = 0.53$.[12] A combined ANOVA of the two groups of participants yielded a significant subdivision effect overall, $F(1, 13) = 14.25, p = .002$, as well as a significant Group × Subdivision interaction, $F(1, 13) = 7.36, p = .018$. Thus, despite (or perhaps because of) their more accurate tempo perception and judgment, musicians tended to show larger perceptual effects of subdivision than did nonmusicians.

REPRODUCTION TASK

The upper left panel in Figure 10 shows the reproduction results for the musicians.[13] As expected, their reproductions were quite accurate in the sub-0 condition, with only a slight tendency to tap faster than the standard sequence at the slower tempi. In the sub-3 condition, by contrast, their reproductions were uniformly slower. The subdivision effect was shown by all musicians and was highly reliable, $F(1, 7) = 26.87, p = .001$. As in Experiment 1, the data are ambiguous as to

[12]Closer inspection of the individual data suggested that nonmusicians could be divided into two groups: the research assistant and two participants who were instructed and run by him, all of whom showed either near-zero or negative effects; and four participants who had been instructed and run by the author, all of whom showed positive effects. This may have been due to more careful instruction; most nonmusicians did not immediately understand the task and required some tutoring. The mean subdivision effect of the latter group, however, was still only about 1.5%, comparable to the smallest effects shown by individual musicians. By contrast, the most advanced musician (a professional flutist) showed the largest effect of all, more than 5%.

[13]The tapping data required some editing prior to analysis because taps sometimes did not register, resulting in ITIs of double length. These were deleted, or replaced if participants had made an extra tap to compensate. Also, there were occasional irregular trials in the nonmusicians' performance, which were deleted as outliers. In the later analysis of the silent intervals preceding reproduction, occasional outliers were likewise omitted.

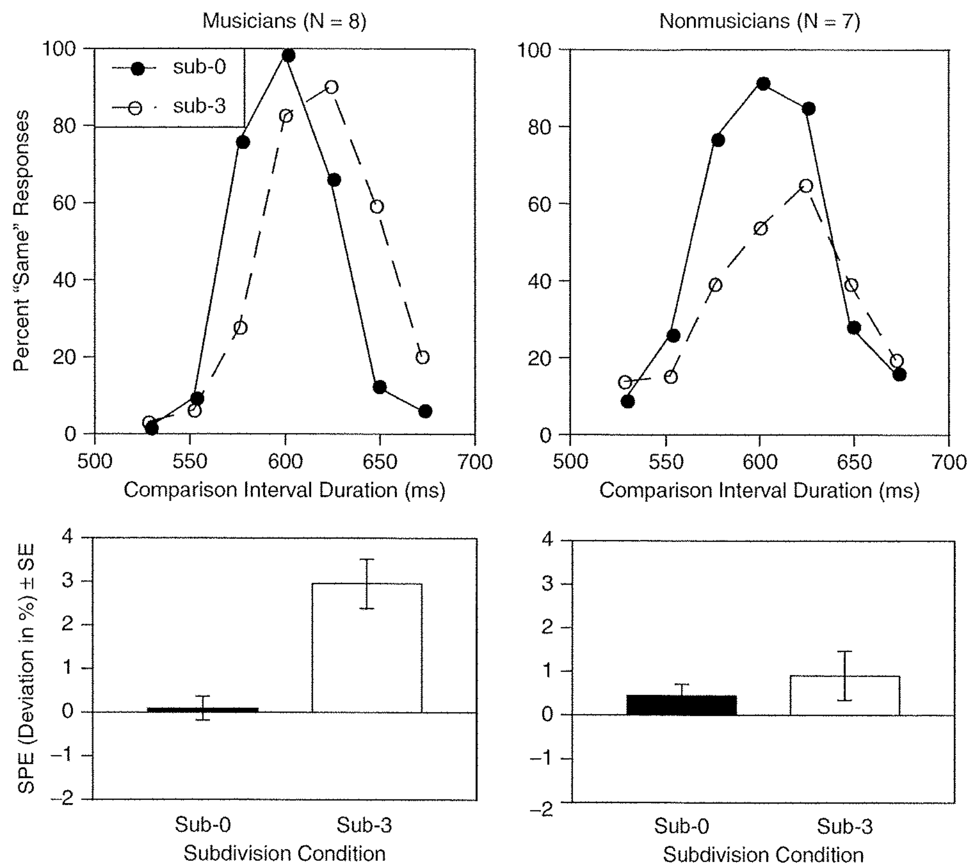

FIGURE 9. Results of the perception task of Experiment 4. Upper panels: Percentages of "same" responses in the two subdivision conditions for musicians and nonmusicians. Lower panels: Deviations of mean points of subjective equality (SPEs) from the target IBI (600 ms), with standard error bars.

whether the subdivision effect is constant or proportional to IBI duration: The Subdivision × IBI interaction was far from significance in ANOVAs on either absolute or relative values. The ITI increment was 29 ms on average (about 5% of the IBI).

Two of the nonmusicians provided tapping data that were too irregular to be analyzed. The results of the five remaining nonmusicians are shown in the upper right panel of Figure 10. Remarkably, they showed a much larger subdivision effect than the musicians, while being sensitive to the target tempo. Moreover, the small standard errors indicate that this large effect size was quite consistent across participants. The mean increment was 62 ms (about 10% of the IBI), and the data are compatible with either constancy or proportionality of the effect. The subdivision effect for the nonmusicians was highly reliable, $F(1, 4) = 104.26$, $p = .001$. A joint ANOVA of the two groups of participants revealed, besides a significant overall effect of subdivision, a significant Group × Subdivision interaction, $F(1, 11) = 14.18$, $p = .003$, which confirms that nonmusicians showed a larger subdivision effect in reproduction than musicians.

The effect of subdivision on the silent interval preceding reproduction was also analyzed. Despite instructions, two of the eight musicians did not consistently skip just one beat between the standard sequence and their reproduction. The remaining six did so, however. For them, the lower panel in Figure 10 shows the silent interval duration as a function of IBI duration in the two subdivision conditions. In the sub-0 condition the silent interval was almost exactly twice the IBI duration, but it increased (by 34 ms on average) in the sub-3 condition, $F(1, 5) = 8.87$, $p = .031$. This increment is similar to the mean ITI increment in reproduction (29 ms), and if that mean is recalculated for the six participants whose data are shown here it becomes 33 ms and matches almost exactly. Note, however, that the present interval is twice as long, so the increment represents only about 2.5% of the IBI. This

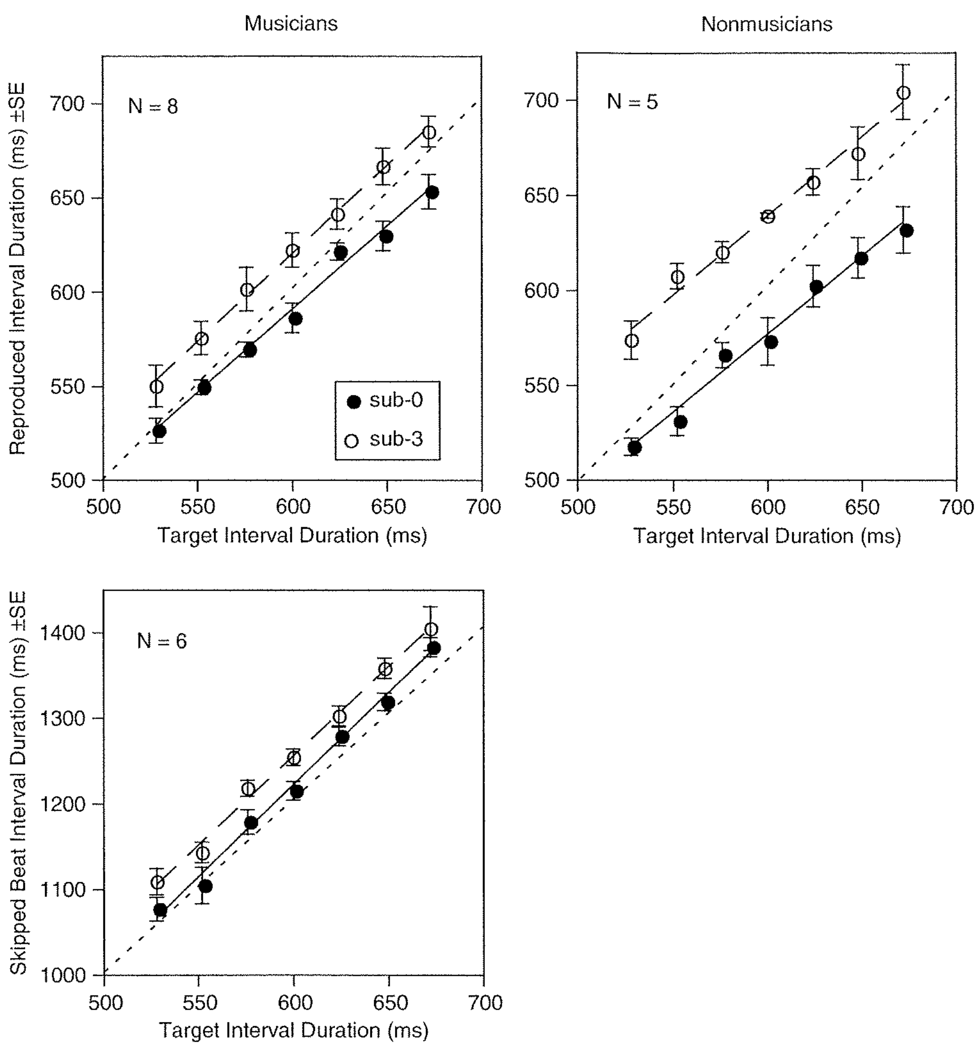

FIGURE 10. Results of the reproduction task of Experiment 4. Upper panels: Mean reproduction IBI duration as a function of standard IBI duration, with standard error bars. Lower panel: The duration of the silent interval before reproduction started as a function of standard IBI duration, for a subset of the musicians who skipped exactly one beat. The dotted diagonal lines indicate what exact reproduction would look like.

suggests that the increment represents a delay of the tap terminating the interval, not the sum of increments in the two IBIs that are implicit in the long interval. Alternatively, however, it may be that the increment in implicit IBIs was only half as large as that in explicit ITIs, or that the first implicit IBI was not affected by subdivision whereas the second one was (which is similar to saying that the tap was delayed).

Only one nonmusician maintained a consistent interval before reproduction, which in his case almost exactly equaled three beats. Remarkably, however, he showed no effect of subdivision on the silent interval, even though he showed a large subdivision effect in his reproduction ITIs. There was also one musician (the author) who showed no effect of subdivision on the duration of the silent interval, even though he showed an effect in reproduction. These two cases suggest that the interval preceding reproduction can be timed independent of the reproduction itself.

It is clear from the above findings that the subdivision effects in perception and reproduction were not positively correlated, as one might have expected. Indeed, across all participants with analyzable data in both tasks ($N = 13$), the correlation was negative, $r(11) = -.41$, though not significant due to the small sample size. Even within each participant group, however, there was no indication of any positive correlation. This suggests that perception and reproduction are not equivalent measures of the subdivision effect.

General Discussion

The present study demonstrates a filled duration illusion in metrical contexts and with musically trained participants: Inter-beat intervals that are metrically subdivided seem to last longer (implying a slower beat tempo) than those that are not subdivided. Experiment 1 showed that duple, triple, or quadruple subdivision during synchronization with a beat has a robust slowing effect on continuation tapping of the beat. Experiment 2 replicated this effect for duple and triple subdivision and showed that self-generated duple subdivisions during synchronization have an effect similar to computer-generated subdivisions; however, the results for triple subdivision at slower tempi were anomalous. The subdivision effect largely disappeared when the same subdivisions were made in continuation tapping. In Experiment 3, an analogous subdivision effect was obtained in a perceptual judgment task, but only for triple and sextuple, not for duple subdivision, and not for all participants. Experiment 4 found a reliable perceptual effect with quadruple subdivision, as well as a robust effect of subdivision on beat tapping in a reproduction task. Nonmusicians, tested only in this last experiment, showed a much larger effect than musicians in reproduction, but a smaller effect in perception.

Experiment 1 also examined whether subdivision during synchronization affects asynchronies in the same way as it affects continuation tapping, as it should according to the perceptual underestimation hypothesis of Wohlschläger and Koch (2000). This hypothesis found little support. Not only were asynchronies practically unaffected by subdivision, but their absolute magnitude also did not correspond to the relative slowing observed during continuation tapping. Furthermore, they were uncorrelated with the tempo of continuation tapping in the cases of triple and quadruple subdivision. In the duple subdivision and baseline (no subdivision) conditions, however, there was a positive correlation, and asynchronies and continuation tapping were also affected similarly by manipulations of beat tempo (IBI duration). Thus, there may still be a perceptual link between synchronization and continuation tapping, but asynchronies seem to depend on other factors as well. Their absolute magnitude may reflect the relative rate of information accumulation from different sensory modalities (Aschersleben, 2002), and subdivisions may serve as additional temporal references in synchronization and thereby reduce the dependence of asynchronies on perception of IBIs (Large e al., 2002; Repp, 2008). Wohlschläger and Koch found that random raindrops reduced the negative mean asynchrony during synchronization, but randomly timed events presumably cannot serve as temporal references. The present participants may have relied less on perceived IBI duration and more on perceived subdivision IOI duration in timing their taps during synchronization. Still, it is curious that their asynchronies changed hardly at all, which suggests that IOI and IBI durations were underestimated by the same absolute amount.

Several other issues are left unresolved by the present study. One is whether the subdivision effect is independent of beat tempo or whether it is a constant proportion of the baseline IBI. The experiments were not specifically designed to address this question, but as far as they go, the results are compatible with either hypothesis. A fixed increment would be consistent with Nakajima's (1987) model of duration perception, except that the effect was much smaller than predicted by that model and did not increase linearly with the number of subdivisions. That may be due to the constraints imposed by a metrical framework and to nonlinearities at short (subdivision) interval durations. Wearden et al. (2007) recently found that the filled duration illusion increases in proportion to the baseline interval duration, which suggested to these authors that filling an interval speeds up the passage of time (i.e., increases the pulse rate in a pacemaker-accumulator model of timing; Gibbon, Church, & Meck, 1984). However, the filled interval was a continuous sound, which is quite different from subdivision of an empty interval by discrete events. It seems more plausible that discrete events will have discrete effects. In any case, this question needs to be investigated further with a wider range of IBI durations.

Another unresolved issue is the curious acceleration in continuation tapping observed in Experiment 2 when triple subdivisions during synchronization were self-produced with feedback tones and the beat rate was slow. This result, which was shown by some but not all participants, remains quite mysterious for the time being.

An intriguing finding in need of explanation and further study is the dissociation between perception and reproduction results in Experiment 4. It is perhaps not surprising that nonmusicians showed a smaller subdivision effect in perception than musicians did because their perceptual judgments are likely to be more variable.

The surprising result is their large subdivision effect in reproduction. It is tempting to attribute this to a high threshold for tempo discrimination, but that is a fallacy: A veridical memory of the beat tempo of the target would be needed to discriminate it from the tempo of the reproduction; however, the reproduction is assumed to reflect the perceived and remembered beat tempo. Nevertheless, the results paradoxically suggest that nonmusicians should be able to judge their own reproductions as being slower than the targets if these sequences were recorded and played back to them. This prediction could be tested in a future experiment.

Additional questions for future research arise from limitations of the present study. First, the subdivisions studied here were simple and isochronous. Would more complex rhythmic subdivisions also slow the perceived beat tempo? This seems likely because similar effects have been obtained with randomly timed raindrops (Caspi, 2002; Wohlschläger & Koch, 2000), and psychophysical studies have found a filled duration illusion with various irregular patterns of subdivisions (Grimm, 1934; Israeli, 1930; Ornstein, 1969; Thomas & Brown, 1974). However, this issue warrants further investigation.

Second, the subdivided part of a sequence (be it a pacing sequence for synchronization, target for reproduction, or standard in a perceptual task) here always preceded the simple part (continuation, reproduction, or comparison). Would the subdivision effect also be observed if these parts occurred in reverse order? Current follow-up experiments examine this question and suggest a positive answer (Repp & Bruttomesso, 2008).

Third, it is currently unknown whether the findings would generalize to music performance that is entirely self-paced. Do musicians speed up slightly when they subdivide a beat and slow down again when they return to a simple beat? The prediction is that they should do this (without noticing it, of course), in order to keep their own beat tempo perceptually constant. It should be noted that the predicted effect is fairly small (3-5% at most) and should not be detectable by either performers or listeners, only revealed by measurements. A constant tempo, however, should lead to the impression of slight dragging during dense passages.

Finally, the role of mental subdivision in the present paradigms remains to be considered. In none of the experiments did the instructions mention mental subdivision, but musically trained participants may have engaged in it anyway, either automatically or deliberately. Mental subdivision during continuation tapping, reproduction, or listening to a comparison sequence would be expected to attenuate the subdivision effect, just as explicit subdivision with the other hand did in Experiment 2. Musicians might show larger effects if they were instructed never to subdivide the beat mentally. The large subdivision effect in nonmusicians' reproduction in Experiment 4 could be due to an absence of spontaneous subdivision. In addition, it might be asked whether mental subdivision alone can generate a subdivision effect. Thus, there are many possibilities for further research along these lines.

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Correspondence concerning this article should be addressed to Bruno H. Repp, Haskins Laboratories, 300 George Street, New Haven, CT 06511-6624. E-MAIL: repp@haskins.yale.edu

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