TAPPING TO A VERY SLOW BEAT: A COMPARISON OF MUSICIANS AND NONMUSICIANS

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WHEN NONMUSICIANS TAP with isochronous auditory tone sequences, the taps typically precede the tone onsets. However, when the tone inter-onset interval (IOI) is increased beyond 2 s, an increasing proportion of taps follows the tone onsets by 150 ms or more. Such responses indicate reactions rather than anticipations, and they have been interpreted as reflecting a rate limit of synchronization related to a temporal limit of auditory working memory. In the present study, musicians and nonmusicians were asked to synchronize their taps with sequences whose IOIs ranged from 1000 to 3500 ms. Nonmusicians showed much larger anticipation errors and higher variability but actually fewer reactive responses than musicians. No clear landmarks of a rate limit for synchronization were observed.

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SENSORIMOTOR SYNCHRONIZATION (SMS) is the coordination of a physical action in time with a rhythmic sequence, and thus is highly important in music performance (Repp, 2006a). Most SMS research uses a simple finger-tapping paradigm, where participants tap along with an auditory sequence of tones (see Repp, 2005c, for a review). Several recent articles have discussed upper rate limits of in-phase (on-beat) and anti-phase (off-beat) tapping (Repp, 2003, 2005a, 2005b, 2006b; see also Bartlett & Bartlett, 1959). On-beat synchronization with an isochronous sequence of tones becomes difficult beyond a certain rate, which for musicians tends to occur at inter-onset intervals (IOIs) of 100 to 125 ms. This is not a biomechanical limit of tapping speed because it holds when the task is to tap with, say, every 4th tone in the sequence. Rather, it probably reflects a temporal window of perceptual integration or attention within which tones are difficult to perceive as individual events. The upper rate limit for off-beat tapping, at IOIs of about 350 ms for musicians, is much lower (higher in terms of IOIs) than that for on-beat tapping. These rate limits or "synchronization thresholds" (Repp, 2003) are well defined by the occurrence of continuous phase drift, indicating an inability to synchronize, or, in the case of off-beat tapping, by a switch to on-beat tapping.

The present study is concerned with the question of whether there is also a lower rate limit of SMS, occurring at long IOIs. It has been noted repeatedly over the years that synchronization becomes subjectively difficult when the IOIs of a slow sequence are in the vicinity of 1.8 s (e.g., MacDorman, 1962; Woodrow, 1932). This interval corresponds to what is often regarded as the upper temporal (i.e., lower rate) limit for rhythm perception beyond which successive tones are perceived as unrelated events (Bolton, 1894; Fraisse, 1982; MacDougall, 1903). Fraisse (1966) noted that there is also a marked increase in the variability of tap-tone asynchronies between IOIs of 1500 and 3000 ms. Furthermore, the limit of "subjective rhythmization"—the spontaneous or deliberate perceptual grouping of successive isochronous sequence events—also seems to be in that range. Bolton (1894) found that subjective rhythmization did not extend beyond IOIs of about 1600 ms, while MacDougall (1903) located the limit between 1500 and 2000 ms. Fraisse (1982), after reviewing the evidence, opted for 1800 ms.

Three more recent studies (Engström, Kelso, & Holroyd, 1996; Mates, Radil, Müller, & Pöppel, 1994; Miyake, Onishi, & Pöppel, 2004) have investigated specifically the lower rate limit of SMS. Mates et al. (1994) used sequences with IOIs ranging from 300 to 4800 ms to investigate how the distribution of tap-tone asynchronies changes over this range of intervals. For the shortest IOI (300 ms), they found a narrow distribution with a mean close to zero. As the IOI increased up to about 1800 ms, the distribution became broader and had an increasingly negative mean, which reflects a well-known tendency for taps to precede sequence tones (see Aschersleben, 2002). At even longer IOIs

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(2400 ms to 4800 ms), the distribution became increasingly bimodal, due to the emergence of taps with positive asynchronies that clustered tightly around about 150 ms (a typical reaction time for auditory stimuli). For the longest IOI tested, 4800 ms, a large majority of the taps was reactive. The authors concluded that around 2-3 s the brain reaches a limit of temporal integration capacity beyond which it is difficult to anticipate the occurrence of the tones, and which causes participants to adopt a reactive strategy.

Miyake et al. (2004) performed a similar experiment but extended the range of IOIs up to 6000 ms. They, too, found that reactive tapping emerged at IOIs of 1800 ms and continued to increase as IOI increased. At the longest IOI, about 60% of taps were reactions. They also found that diversion of attention from the tapping task by a simultaneous word memory task increased the frequency of reactive taps at long IOIs. Miyake et al. concluded that for IOIs up to 1500 ms, the timing mechanism does not require attention, whereas at longer intervals attentional resources are required for anticipation of the sequence tones.

Engström et al. (1996) took a somewhat different approach, informed by dynamic systems theory. Using a visual metronome with IOIs ranging from 727 to 8000 ms and a finger flexion task (i.e., tapping in the air), they compared a synchronization condition with a condition in which participants were actually instructed to react to the stimuli. The synchronization results resembled those of Mates et al. (1994) and Miyake et al. (2004), although reactive responses emerged sooner (at an IOI of 1333 ms). In the reactive condition, all taps at long IOIs were reactions, but anticipatory taps began to emerge and increased in frequency as the IOI got shorter than about 2000 ms. In addition, Engström et al. included a task in which participants had to flex their finger in anti-phase with the stimuli. In this condition, the distribution of responses around the IOI midpoint remained unimodal across all IOIs tested because there was no stimulus to react to in the vicinity of the taps.

The notion of a lower rate limit of SMS thus has been linked to the emergence of reactive responses, although the increase in their proportion with IOI is very gradual. It has also been suggested that the rate limit reflects a temporal limit of attention or short-term memory. Older psychological literature often talks about the specious present (James, 1890) or psychological present—"the time interval, a few seconds in length, in which we experience the flow of events as being simultaneously available to perceptual or cognitive analysis" (Michon, 1978, p. 90). Fraisse (1984) stated that the *perception* of duration occurs only within the psychological present, lasting 2-3 s on average, duration being "a quantity whose beginning has not yet been stored in memory" (p. 10). By contrast, longer durations must be *estimated* on the basis of memory traces, according to Fraisse. More recently, Pöppel (1997) has argued for a neural mechanism that "binds successive events of up to 3 s into perceptual units" (p. 58; see also Pöppel, 2004; Wittmann & Pöppel, 2000).

The memory literature provides additional evidence of such a temporal limit. Schweickert and Boruff (1986) estimated the duration of short-term memory for verbal material (the "verbal trace") by considering the time it takes to pronounce a memorized list and arrived at a mean duration of 1.88 s. The phonological working memory postulated in the well-known theory of Baddeley (1986; Baddeley & Hitch, 1974) is likewise said to have a temporal span of 1.5 to 2 s, and Miyake et al. (2004) specifically related their SMS results to Baddeley's theory. Interestingly, recent research suggests that the phonological store is not specific to verbal material, as originally believed, but is also employed in the processing of rhythms (Grube, 1996, 1998; Larsen & Baddeley, 2003; Saito, 1993, 1994, 2001; Saito & Ishio, 1998; Wilson, 2001). The same memory limit may also account for the poor identifiability of familiar melodies when they are slowed down (Warren, Gardner, Brubaker, & Bashford, 1991).

A temporal limit of SMS and a possibly related limit of working memory for rhythm are clearly relevant to music activities. Although it is rare for musicians to have to coordinate extended rhythms with IOIs longer than 2 s, rests of several seconds duration requiring extrapolation of a previous beat are not uncommon, at least in serious music. Entries following such long rests are notoriously difficult to coordinate without the help of visual cues provided by other players or a conductor.

The SMS results reviewed above (Engström et al., 1996; Mates et al., 1994; Miyake et al., 2004) were obtained from participants who apparently were not musically trained.[1] The primary aim of the present study was to investigate whether music training affects the lower rate limit of SMS reflected in the emergence of reactive responses at long IOIs. Because synchronization, memory for rhythm and temporal intervals, and

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[1] None of the authors mentions musical training. Yoshihiro Miyake (personal communication, December 24, 2005) has confirmed that his participants were not musically trained.

perceptual integration over large time spans are all required in musical activities, music training may help to extend the temporal range of working memory that is reflected in the lower rate limit of SMS. Results supporting this hypothesis would demonstrate that the rate limit is flexible and subject to learning. By contrast, results showing no difference between musicians and nonmusicians would suggest that the limit is relatively fixed and hard-wired.

The musicians we tested were also experienced in laboratory synchronization tasks, whereas the nonmusicians were not. However, the nonmusician participants of Mates et al. (1994) and Miyake et al. (2004) had tapping experience, which made them suitable additional groups for comparison.

Our study had two secondary purposes, for the group of musicians only. First, we also included an off-beat tapping condition in order to replicate the findings of Engström et al. (1996) in a finger tapping (rather than finger flexion) task with auditory (rather than visual) stimuli. Like Engström et al., we did not expect to find any reactive tapping because there is no stimulus to react to when taps fall in the middle of IOIs between tones. The results of Engström et al. (in their Figures 9 and 11) suggest that anti-phase coordination was more variable than in-phase coordination, which is a common finding in the literature on motor coordination. We hypothesized, on the contrary, that musicians' off-beat tapping would be more accurate than their on-beat tapping because of the metrical subdivision it involves. It is well known that timing variability increases with interval duration (e.g., Peters, 1989; Madison, 2001), and having to delay taps by only IOI/2 after each tone may well lead to greater timing precision than having to delay taps by a full IOI.

Second, in both the on-beat and off-beat tapping conditions, we presented musician participants not only with monotone sequences of high-pitched tones but also with sequences consisting of a mid-register ascending and descending C major scale, played with legato articulation. We wondered whether synchronization would be facilitated by a melodic auditory stimulus and whether the rate limit of SMS would consequently be extended in melodic sequences. MacDougall (1903), in discussing the lower rate limit for perception of rhythm, commented that "a certain voluminousness is indispensable to the support of such slow measures. The limit is reached sooner when the series of sounds is given by the fall of hammers on their anvils than when a resonant body like a bell is struck, or a continuous sound is produced upon a pipe or a reed" (pp. 322-323). A mid-register legato scale is both more continuous and more voluminous than a series of high-pitched tones and therefore may facilitate the perceptual integration of the successive tones into a slow rhythm with which taps can then more easily be synchronized.

Method

Participants

The musician participants included six paid volunteers (five women; ages 19-24) and the authors (ages 60 and 20, respectively). All had extensive musical training (ranging from advanced amateur to professional level, with a minimum of 7 years of instruction) and included two violists, one cellist, one flutist (no longer active), one clarinetist, one bassoonist, one percussionist, and one pianist. They were all regular participants in synchronization experiments.

The nonmusician participants included ten paid volunteers, recruited by advertisement on Yale campus or by direct invitation, and two unpaid volunteers from Haskins Laboratories (five women; ages 18-29, except for one participant who was 56). Only two had previously participated in a synchronization experiment. One female participant's data had to be excluded because a substantial number of her taps had not been registered.

Materials

Two sets of isochronous sequences were constructed, referred to here as tone sequences and scale sequences. Tone sequences consisted of 30 identical high-pitched digital piano tones ($E^{b}7$, 2489 Hz, decaying freely), while scale sequences consisted of an ascending and descending C major scale, repeated once, for a total of 29 tones. The scale ranged from C4 (262 Hz) to C5 (523 Hz). Each of the scale tones was specified to end 10 ms after the next tone began, which resulted in a legato style of articulation. All tones were presented at a constant MIDI velocity of 60.

There were eleven versions of each sequence that differed in IOI. The IOIs ranged from 1000 to 3500 ms in steps of 250 ms. We did not include even longer IOIs in order to reduce the length and boredom of the experiment, and also because we wanted to focus on the region within which the rate limit was expected to be located. The sequences were grouped into blocks of 11 randomly ordered trials. They were played as MIDI files on a

Roland RD-250s digital piano that was controlled by a program written in MAX 3.0.9 and running on an Apple iMac G4 computer. The same program recorded the participants' taps.

Procedure

Musicians came for four one-hour sessions, typically one week apart. They wore Sennheiser HD540 II headphones and sat in front of the computer while holding a Roland SPD-6 percussion pad on their lap. In the on-beat tapping condition (Sessions 1 and 2), they were instructed to tap with the index finger of their preferred hand in synchrony with the tones in each sequence, starting with the third tone. The impact of the taps on the rubber surface was audible as a thud. Participants were instructed not to subdivide the IOIs by means of movement or covert counting. In the off-beat tapping condition (Sessions 3 and 4), participants were asked to tap at the midpoint of the IOIs between successive tones, starting after the second tone. During each session they completed four blocks of trials. The blocks alternated between tones and scales, always starting with a block of tone sequences. Participants started trials by pressing the space bar on the computer keyboard. There were short breaks between blocks during which the recorded data were saved.

Nonmusicians came for a single session in which they received four blocks of tone sequences and were given on-beat tapping instructions. The procedure was the same as for the musicians, but without specific instructions not to subdivide.

Results

On-beat Tapping: Musicians vs. Nonmusicians

Tone-tap asynchronies for on-beat tapping were computed in the conventional manner, such that a negative asynchrony means that the tap preceded its target tone. Figure 1A shows the mean asynchronies of musicians and nonmusicians as a function of IOI duration. The asynchronies were remarkably different for the two participant groups, making statistical analysis superfluous. Whereas musicians showed only very small negative asynchronies that changed little as a function of IOI, nonmusicians' mean asynchrony was about −40 ms at the shortest IOI and decreased almost linearly to about −150 ms at the longest IOI. The nonmusicians' results resemble those reported by Mates et al. (1994) and Miyake et al. (2004), although two of the Mates et al. participants showed small asynchronies.

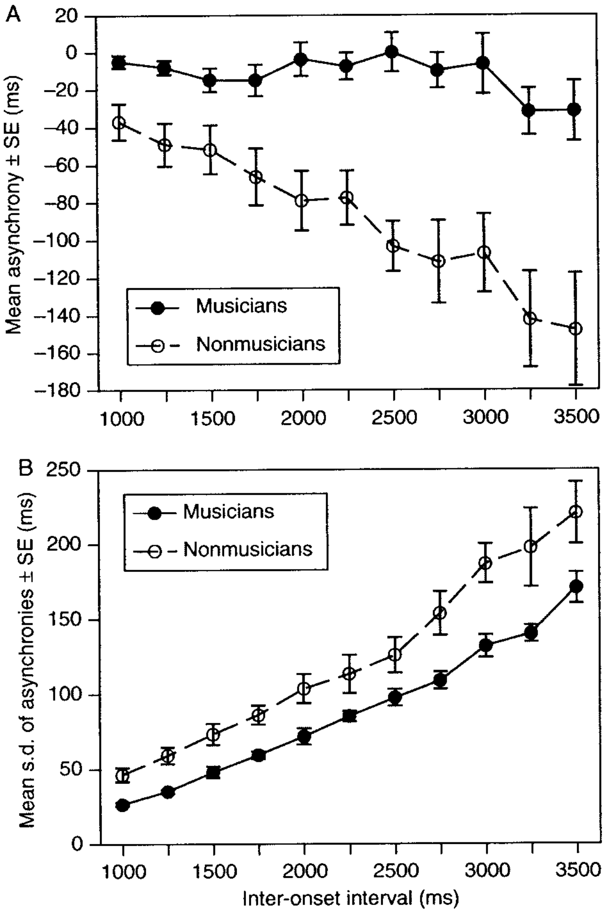

FIGURE 1. (A) Mean asynchronies and (B) mean within-trial standard deviations as a function of IOI duration for on-beat tapping with tone sequences.

Figure 1B shows the corresponding mean within-trial standard deviations of asynchronies. These data were subjected to a mixed-model ANOVA with the variables of group and IOI.[2] As expected, variability increased with IOI duration, $F(10,170) = 90.77$, $p < .0001$. The musicians' performance was less variable than that of the nonmusicians at all IOIs, $F(1,17) = 7.46$, $p < .02$. Between IOIs of 1000 and 2500 ms, the increase in variability was strongly linear for both groups. Beyond 2500 ms, nonmusicians showed a steeper increase in variability, and musicians also showed a tendency in that direction. Polynomial decomposition of the effect of IOI revealed significant linear and quadratic components, $F(1,17) = 154.18$, $p < .0001$, and $F(1,17) = 17.73$, $p < .001$, respectively, and there was no significant interaction with group.

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[2] The Greenhouse-Geisser correction was applied to all F values with more than one degree of freedom in the numerator.

The linear function between IOIs of 1000 and 2500 ms very nearly followed Weber's law for nonmusicians (the coefficient of variation showed only a small increase from 4.6% to 5.0%), whereas for musicians it deviated somewhat more (the coefficient of variation increased from 2.7% to 3.9%). Mates et al. (1994) reported the standard deviations of inter-tap intervals rather than asynchronies. For four of their five participants, the standard deviations increased linearly within the range studied here, and the coefficient of variation increased as well.

Frequency distributions of asynchronies for each IOI duration were obtained by combining data from all participants within each group. The distributions exhibited the expected characteristics: In addition to a general broadening as IOI increased, a visible "bump" centered between 150 and 200 ms began to emerge in the distributions for the longer IOIs. Following Miyake et al. (2004), we considered all taps with asynchronies greater than 100 ms to be reactive responses.

Figure 2A shows the mean percentages of reactive responses as a function of IOI duration for musicians and nonmusicians. Also included are the data of Miyake et al. for the present range of IOIs. It is evident that reactive responses increased with IOI, as expected, $F(10,170) = 33.25, p < .0001$, but they increased faster for musicians than for nonmusicians, with the Miyake et al. data (for nonmusicians with tapping experience) falling roughly in between. Although the main effect of group did not reach significance, $F(1,17) = 3.73, p < .07$, the Group x IOI interaction was significant, $F(10,170) = 4.09, p < .02$. Although this difference between musicians and nonmusicians had not been predicted, it can be readily understood from the changes in mean asynchrony and variability with IOI (Figure 1). Figure 2B plots the percentages of reactive responses predicted from the mean asynchrony and mean standard deviation of each participant group at each IOI under the assumption that the asynchronies have a normal distribution. These predictions are slightly lower than the obtained percentages but match their pattern very closely. Thus, although reactive responses tend to cluster around values typical of reaction times, they merely represent the shortened tail of a normal distribution; no special strategy of reacting to the tones needs to be assumed.

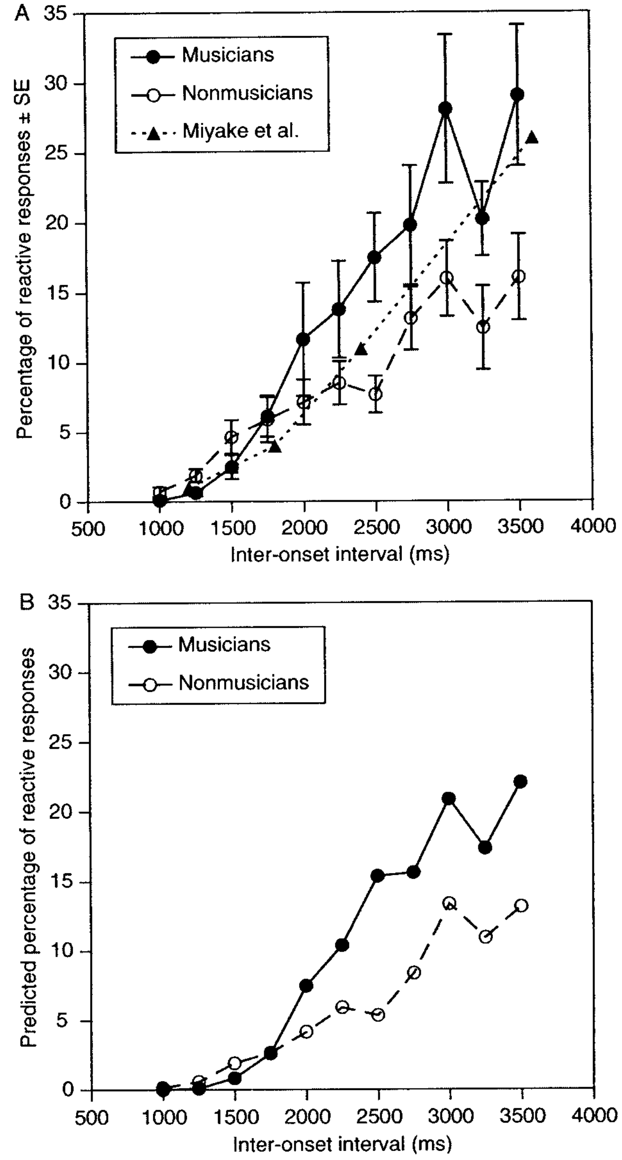

FIGURE 2. (A) Mean percentage of reactive responses (asynchronies greater than 100 ms) as a function of IOI duration for on-beat tapping with tone sequences. Also shown are the data of Miyake et al. (2004), estimated from their Figure 3, right-hand panel, condition "N". (B) Predicted percentages of reactive responses based on grand means and standard deviations, and assuming a normal distribution of responses.

As an additional measure of synchronization performance, the lag-1 autocorrelation (AC-1) was computed for both asynchronies and inter-tap intervals (ITIs) within each trial. The AC-1 is normally positive for asynchronies but negative for ITIs (Semjen, Schulze, & Vorberg, 2000). Moreover, the efficiency of phase correction in synchronization increases as IOI increases, and this leads to a decrease in both autocorrelations (i.e., the former becoming less positive and the latter becoming more negative). Although these trends have been demonstrated only for a range of relatively short IOIs (Semjen et al., 2000), we thought the AC-1 measures might possibly indicate a change in

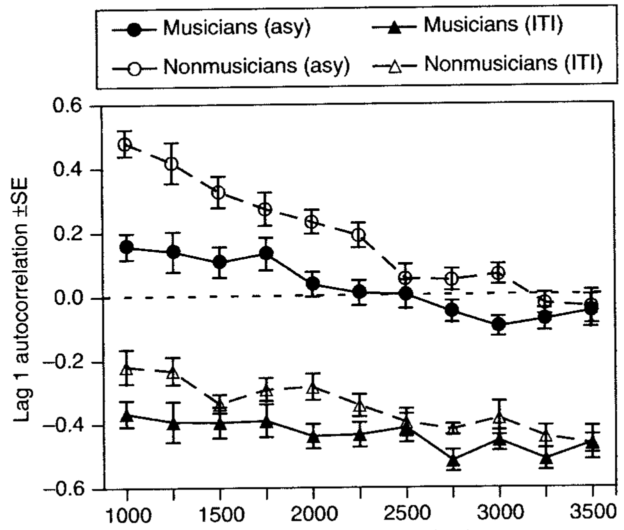

FIGURE 3. Mean lag-1 autocorrelations for asynchronies (asy) and for inter-tap intervals (ITI) as a function of IOI duration for on-beat tapping with tone sequences.

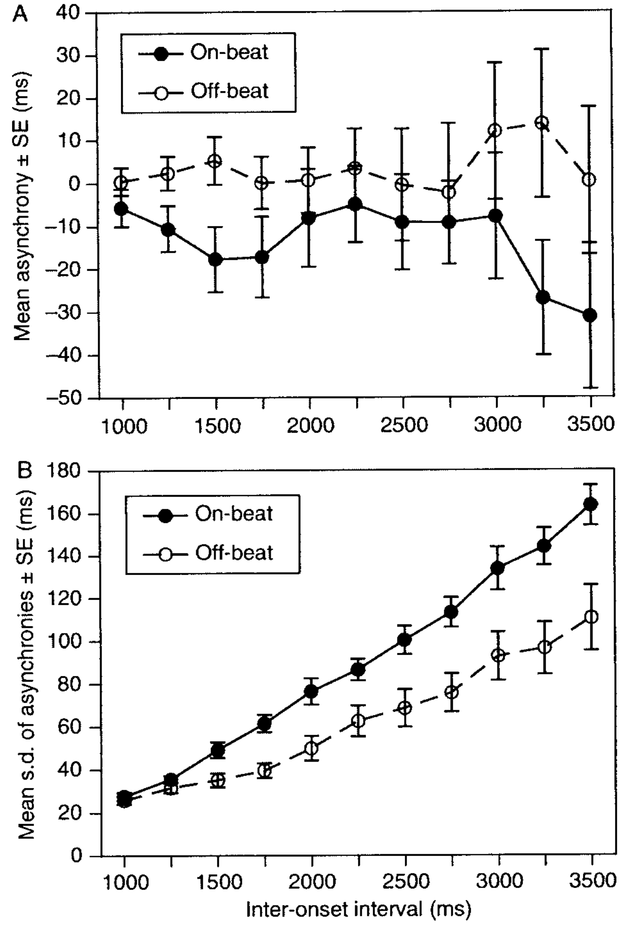

FIGURE 4. (A) Mean asynchronies and (B) mean within-trial standard deviations as a function of IOI duration for tone and scale sequences combined in on-beat and off-beat tapping conditions for musicians..

error correction strategy at the rate limit of synchronization.

Figure 3 shows the mean values of AC-1 for asynchronies and ITIs as a function of IOI duration for the two participant groups. Both coefficients decreased as IOI increased, $F(10,270) = 18.53$, $p < .001$, and $F(10,270) = 5.94$, $p < .001$, respectively, which suggests increased efficiency of phase error correction at long IOIs. Musicians showed lower values of the AC-1 coefficient for asynchronies than nonmusicians, $F(1,17) = 12.53$, $p < .003$, which indicates better phase error correction. However, the group difference decreased as IOI increased, $F(10,270) = 4.03$, $p < .005$. There were no significant group differences in the AC-1 for ITIs. The AC-1 functions do not show any clear discontinuity that could be interpreted as marking a rate limit of synchronization.

Off-beat vs. On-beat Tapping and Tones vs. Scales in Musicians

Asynchronies in the off-beat tapping condition were computed relative to the IOI midpoint. Figure 4A compares the mean asynchronies for musicians' on-beat and off-beat tapping. The results for tone sequences and scale sequences have been combined here. It can be seen that, if anything, off-beat tapping was even more accurate than on-beat tapping. A repeated-measures ANOVA with the variables of tapping condition, sequence type, and IOI revealed no significant effects.

Figure 4B compares the mean standard deviations of on-beat and off-beat tapping, again for both sequence types combined. The variability of off-beat tapping, like that of on-beat tapping, increased almost linearly with IOI, but it was smaller overall, $F(1,7) = 55.24$, $p < .001$, because it increased less steeply. Thus the difference between on-beat and off-beat tapping was most pronounced at long IOIs, as reflected in a significant Condition x IOI interaction, $F(10,70) = 8.18$, $p < .008$. The more gradual increase for off-beat tapping also means that the off-beat tapping data conform more closely to Weber's law, with coefficients of variation increasing from 2.6% to 3.2%.

Discussion

A Lower Rate Limit of SMS?

The main purpose of our study was to determine whether musically trained individuals differ from musically untrained participants in their ability to synchronize accurately with slow isochronous auditory sequences. We thought that any such difference would be reflected mainly in lower percentages of reactive responses at long IOIs, which then could be interpreted as reflecting an extended temporal range of auditory working memory. Contrary to this expectation, musicians actually tended to have higher percentages of reactive responses than nonmusicians. However, this should certainly not be interpreted as a lesser capacity of auditory working memory.

Musicians and nonmusicians differed in their mean asynchronies and standard deviations. Musicians showed hardly any anticipation tendency (negative mean asynchrony), whereas nonmusicians tapped further and further ahead of the tones as the sequence tempo became slower. Nonmusicians also showed greater variability than musicians. Assuming a normal distribution of asynchronies, the obtained percentages of reactive responses for both participant groups could be predicted fairly accurately from the means and standard deviations. This means that reactive responses were about as frequent as expected by chance, given the distribution of asynchronies. The clustering of reactive responses between 150 and 200 ms observed in earlier studies, and here as well, is probably due to an acceleration of responses that would have occurred even later in the absence of a tone. Although these responses do represent reactions, they do not seem to reflect any deliberate reactive strategy and therefore cannot be regarded as marking any rate limit of synchronization. The fact that they begin to emerge between 1500 and 2000 ms is merely a consequence of the increasing variability of tap timing.

This is not to deny that participants could adopt a reactive strategy at long IOIs in order to reduce variability. However, the essence of a synchronization task is prediction, not reaction. A reactive strategy basically means abandoning prediction because it is too difficult or too inaccurate. With appropriate instructions and motivation, however, it should be possible to maintain a predictive strategy even at very long IOIs. Some participants in the study of Miyake et al. (2004) seem to have done that. Because a reactive strategy depends on motivation and instructions, it is not a good indicator of a perceptual or memory limit.

The conclusions with regard to the main purpose of this study are thus somewhat disappointing: There is no clear lower rate limit of SMS, and therefore the effect of musical training on the rate limit cannot be assessed.[3] However, the data do show very nicely that musicians are able to distribute their responses around the time of occurrence of the target tones, whereas nonmusicians are prone to a strong anticipation tendency that presumably reflects a persistent underestimation of the IOI duration (Wohlschläger & Koch, 2000). In addition, musicians' taps are less variable, and their serial correlation suggests more effective error correction.

Interval Subdivision

Our study addressed two secondary questions. With regard to one of these—the difference between tone sequences and scale sequences—the findings were entirely negative. The more musical and connected character of the scale sequences did not facilitate SMS in any way, *pace* MacDougall (1903). With regard to the other question, however—the difference between on-beat and off-beat tapping—the results were more interesting. As predicted, and contrary to the findings of Engström et al. (1996), off-beat tapping was less variable than on-beat tapping. More precisely, the variability of on-beat and off-beat tapping was about the same at the shortest IOIs (1000 and 1250 ms), but then a difference emerged and increased with IOI duration. In studies of inter-limb coordination it is common to find that anti-phase coordination is less stable than in-phase coordination, and this is demonstrated by a phase transition from anti-phase to in-phase as the movement frequency is increased (Haken, Kelso, & Bunz, 1985). Such a phase transition can also be observed in tapping with an auditory beat of increasing frequency (Kelso, DelColle, & Schöner, 1990). However, when the beat is relatively slow (IOI > 600 ms), anti-phase tapping can be more stable than in-phase tapping (Semjen, Schulze, & Vorberg, 1992). The reason is that the alternation of beats and taps effectively doubles the event frequency and thereby shortens the interval duration to be timed, with a resulting decrease in variability (Peters, 1989; Wing, 1980). The failure of Engström et al.

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[3] Subjectively, synchronization does seem to get more difficult at IOIs longer than about 2 s, which is the observation reported by early investigators that led to the idea of a lower rate limit of SMS (see Introduction). However, it remains to be seen how abrupt this subjective increase in difficulty is. Quite possibly, it will be found to be as gradual as that of variability. Unfortunately, we missed an opportunity to collect subjective difficulty ratings in this study.

(1996) to find such a difference is probably due to the fact that the taps in their study neither made contact with a surface nor produced a sound. Therefore, they could not easily be integrated with the sequence tones into a composite rhythm.

Although off-beat tapping required binary subdivision of the IOIs, variability did not decrease to the level of on-beat tapping with a sequence having half the IOI duration. For example, off-beat tapping at IOI = 3000 ms was about as variable as on-beat tapping at IOI = 2250 ms and more variable than on-beat tapping at IOI = 1500 ms (see Figure 4B). This may reflect less salient error feedback in the off-beat tapping condition (i.e., large rather than small tap-tone asynchronies), as well as incomplete integration of the different sounds of tones and taps.

The lower variability of off-beat than on-beat tapping raises the more general question of whether implicit or explicit subdivision of IOIs would facilitate SMS with slow sequences. The musician participants were explicitly instructed not to subdivide because it was suspected that they might have various strategies at their disposal that should not be allowed at this point, but that might be investigated more systematically in the future. The nonmusicians, on the other hand, were not instructed not to subdivide because it was thought better not to draw their attention to that possibility. Informal comments of several participants suggested, however, that they spontaneously had adopted strategies such as imagining music along with the tone sequence. It is possible that the nonmusicians' performance would have been even poorer if such strategies had been prohibited.

Although we are currently not able to investigate the effects of subdivision further, one of us (BHR, who is musically trained and has extensive tapping experience) has attempted to get a preview of possible future findings by running himself in three additional sessions (four blocks of tone sequences each) on consecutive days, about 15 months after participating in the original sessions. In the first session, he explicitly subdivided the IOIs by tapping twice as fast as the sequence (2:1 tapping). In the second session, he mentally subdivided the IOIs by imagining an intervening beat while tapping on the beat (1:1 tapping). In the third session, he replicated the original on-beat tapping condition, avoiding mental subdivision. Figure 5 shows the variability results together with those for tone sequences in BHR's original on-beat and off-beat tapping sessions. It can be seen that explicit subdivision led to a clear reduction in the variability of asynchronies, similar to that in off-beat tapping but patterned differently as a function of IOI. Mental subdivision led to a smaller reduction in variability. The final on-beat tapping session replicated the results of the original on-beat session almost exactly, except for one data point (IOI = 3000 ms), which shows that BHR's performance had not simply improved in the intervening 15 months. These data are sufficient to demonstrate that subdivision can indeed reduce variability. What remains to be shown is that it reliably does so in appropriately instructed participants.

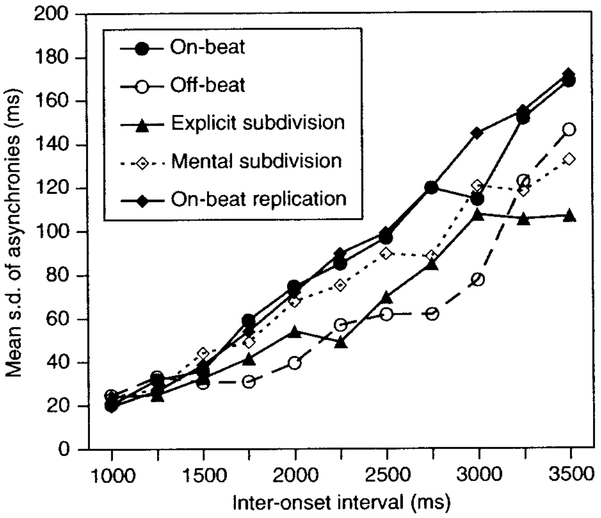

FIGURE 5. Mean within-trial standard deviations as a function of IOI duration in five conditions for author BHR.

In summary, although the present study failed to find evidence for a lower rate limit of SMS, it succeeded in documenting clear differences between musicians and nonmusicians in synchronization ability and raised interesting questions for further research concerning the role of subdivision in synchronization with a slow beat.[4]

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[4] A recent review of rate limits of synchronization (Repp, 2006b) does not reflect the conclusions of the present study because at the time the results for nonmusicians were not yet available.

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