SELF-GENERATED INTERVAL SUBDIVISION REDUCES VARIABILITY OF SYNCHRONIZATION WITH A VERY SLOW METRONOME

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SUBDIVISION BY COUNTING HAS BEEN SHOWN TO improve interval discrimination for durations exceeding 1.2 s (Grondin, Meilleur-Wells, & Lachance, 1999). The present study examined whether simple interval subdivision (bisection) reduces variability of synchronization with a slow metronome. Interval durations ranged from 1 s to 3.25 s. Musically trained participants tapped in synchrony with the metronome while: (1) refraining from any subdivision, (2) mentally bisecting each interval, (3) making additional taps at the bisection points (double tempo tapping), or (4) tapping only at the bisection points (anti-phase tapping). In each task, the standard deviation of asynchronies and intertap intervals was found to increase almost linearly with interval duration, but the slope decreased from condition 1 to condition 4. Differences among conditions were nearly absent with intervals of 1 s (roughly consistent with Grondin et al., 1999), but emerged and increased steadily as interval duration increased. In double tempo tapping, anti-phase taps were less variable than in-phase taps and depended less on the immediately preceding taps. The findings are interpreted in terms of multiple temporal references in synchronization, and their potential relevance to musical ensemble playing is pointed out.

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Key words: synchronization, subdivision, tapping, interval timing, timing variability

A UBIQUITOUS FINDING IN RESEARCH ON TIMING is that temporal variability increases with interval duration (e.g., Getty, 1975; Madison, 2001; Peters, 1989). This problem is familiar to musicians: When playing in an ensemble, it is difficult to be together right after a long note or rest in the music. Often visual cues from other players or a conductor are used in that case to ensure precise coordination. When such cues are not available, another possibly helpful strategy is to subdivide the long interval in some way, for example by counting silently. But does subdivision really help?

Grondin, Meilleur-Wells, and Lachance (1999) investigated the benefits of subdivision by counting in the context of an interval discrimination task. (See also Getty, 1976; Grondin, Ouellet, & Roussel, 2004.) Participants listened to two intervals delimited by short tones and had to tell whether the second interval was shorter or longer than the first. They were instructed to either just listen to the intervals or to count rapidly (or, sometimes, at a prescribed tempo) during each interval. Counting improved discrimination performance regardless of counting tempo, but only if the intervals were longer than about 1.2 s. In the absence of counting, variability of judgments clearly increased with interval duration, but counting reduced that increase substantially.

Grondin et al. (1999) acknowledge that their participants may have discriminated intervals by relying on the final count they reached in each interval, or on when the final tone sounded during the counting. Thus, their results presumably reflect the variability of the counting process as well as that of interval timing (see Killeen & Weiss, 1987). Their findings cannot easily be generalized to music because the rate of counting was unrelated to interval duration, whereas musicians generally subdivide long intervals in music according to a metrical scheme that has been induced by previous context. However, the 1.2 s limit of the observed subdivision benefit may have some relevance to musical practice.

Recently, Grondin and Killeen (2009) compared musicians' and nonmusicians' accuracy in an interval reproduction task that involved counting and singing during the intervals. Nonmusicians' reproduction accuracy was much improved by these filler activities, and musicians performed even better than nonmusicians. However, only nonmusicians were given a condition in which they were asked to refrain from counting or singing because the authors thought that musicians might have difficulty suppressing subdivision strategies or might even employ harmful counter-strategies. Thus, the benefit of these time-keeping activities could not be determined for musicians. Moreover, the interval durations in that study (6–24 s) were much longer than those commonly encountered in music.

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The aim of the present study was to determine whether self-generated subdivision of the simplest kind, namely interval bisection, would be helpful in increasing musicians' synchronization with a slow metronome.[1] This issue was investigated in the context of a synchronization task because synchronization is relevant to coordination in musical ensemble performance, much more so than explicit timing judgments or reproduction of single intervals, although synchronization does involve serial interval reproduction. The research extends previous work by Repp and Doggett (2007), who investigated musicians' and nonmusicians' synchronization of finger taps with slow isochronous sequences having interonset interval (IOI) durations ranging from 1 s to 3.5 s. Although mental subdivision of the long intervals might have been helpful, the musicians were instructed to refrain from such strategies, because it was thought that this might give them an unfair advantage over nonmusicians, who are likely to be less adept in that regard. The nonmusicians were not given any instructions regarding subdivision, and indeed some reported imagining music while tapping. Nevertheless, they performed much more poorly than the musicians in terms of synchronization accuracy and variability.

Although Repp and Doggett (2007) did not investigate the potential benefit of mental subdivision, they did compare in-phase (IP, on-beat) tapping with anti-phase (AP, off-beat) tapping, in musicians only. AP tapping overtly subdivides the metronome intervals into two (more or less) equal parts. AP tapping was found to be less variable than IP tapping, and this difference increased with IOI duration. However, there was no difference at the shortest IOIs (1–1.25 s), which may be related to the 1.2 s limit of the subdivision benefit discovered by Grondin et al. (1999).

The present experiment attempted to replicate this benefit of overt subdivision by comparing IP and AP tapping, but it also included two additional conditions: mental subdivision (MS) and double tempo (DT) tapping, which amounts to tapping both with the metronome and in the middle of the intervals. DT tapping thus can be regarded as IP and AP tapping combined. MS (during IP tapping) involves the generation of internal events at interval midpoints, which may be imaginary sounds or movements, or both. A schematic diagram of all four tasks appears in Figure 1. The questions of interest were, first, whether MS would reduce variability of tap-tone asynchronies and intertap intervals relative to IP tapping without MS, and second, whether DT and AP tapping (forms of overt subdivision) would be even more effective in that respect than MS. A third question was how the subdivision benefit due to DT tapping would compare with that generated by AP tapping. Because intertap intervals are twice as long in AP than in DT tapping, one might expect AP tapping to be more variable than DT tapping. The opposite prediction could also be made, however, because in AP tapping the intervals between preceding tones and taps are consistently short (i.e., half the interval duration), whereas in DT tapping they alternate between long and short, which might cause odd-numbered (IP) taps to be more variable than even-numbered (AP) taps. The results of this comparison thus were expected to provide information about the temporal references that govern tap timing in DT and AP tapping.[2]

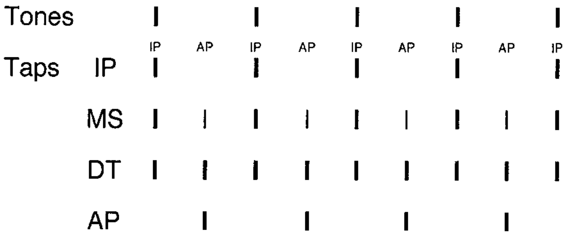

FIGURE 1. Schematic diagram of the four tapping tasks (IP, MS, DT, AP). Thick bars represent tones or taps; thin bars (MS) are mental subdivisions.

Although variability was the dependent variable of main interest, an effect of subdivision on mean asynchronies could also be predicted. Wohlschläger and Koch (2000) reported that making a small finger movement between taps reduces the commonly found anticipation tendency (negative mean asynchrony) in synchronization with a metronome. They attributed this to a reduction of interval underestimation through subdivision, but there are some problems with this hypothesis (see Repp, 2008a). Nevertheless, DT tapping, and perhaps even IP tapping with MS, might be expected to show smaller negative asynchronies than IP tapping without subdivision. Furthermore, the present data were expected to provide useful information about the shape of the

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[1] A benefit due to self-generated subdivisions must be distinguished from a benefit due to externally generated rhythmic subdivisions (Repp, 2003). The present study is concerned only with the former.

[2] In the discussion section of their article, Repp and Doggett (2007) reported pilot data obtained from the first author suggesting that, for him at least, MS reduced variability relative to IP tapping, and DT and AP tapping reduced variability further, with no consistent difference between those two conditions. Differences among the conditions increased with IOI duration but were not evident at the shortest IOIs (1–1.75 s). At the time, data from additional participants could not be collected because of a hiatus in grant support.

function relating variability to IOI duration in a range of durations that has not been much investigated, especially in a synchronization task (but see Madison, 2001). A linearly increasing function would indicate that variability follows a generalized Weber's law (Getty, 1975; Ivry & Hazeltine, 1995).

Method

PARTICIPANTS

Six graduate students from the Yale School of Music, who were paid for their services, and the author participated. The students (two men and four women, 22–26 years old) were highly skilled on their primary instruments (piano-2, violin, viola, double bass, harp; 13–23 years of training) and were regular participants in synchronization experiments, albeit not ones using very slow metronomes. The author, an amateur pianist, was 64 years old and was the only one who had previously tapped with very slow metronomes, in the Repp and Doggett (2007) study several years ago.

MATERIALS AND EQUIPMENT

Each trial consisted of a sequence of 30 tones with a constant IOI. IOI duration varied between trials and assumed one of 10 values ranging from 1 s to 3.25 s in steps of 0.25 s. A block of trials comprised 10 randomly ordered trials, each with a different IOI duration.[3]

Stimulus generation and data collection were controlled by a program written in MAX 4.3.6, running on an Intel iMac computer. The metronome tones (C4, piano timbre, 40 ms duration) were produced by a Roland RD-250s digital piano according to musical-instrument-digital-interface (MIDI) instructions generated by the MAX program and were presented over Sennheiser HD540 reference II headphones at a comfortable intensity. Participants tapped on a Roland SPD-6 percussion pad, held on their lap.

PROCEDURE

Participants completed four one-hour sessions on separate days, typically one week apart. In each session, they were given four blocks of trials, one for each experimental condition (IP, MS, DT, AP). The order of conditions for each participant was counterbalanced across sessions according to a 4 × 4 Latin square, and each participant started with a different order in Session 1. Participants started a block by clicking a virtual button on the computer screen and started each trial by pressing the space bar on the computer keyboard. They tapped with the index or middle finger of their preferred hand (the right hand in all cases). The impact of the finger on the pad was audible as a thud. There were short breaks between blocks during which the recorded data were saved.

The following instructions were displayed on the computer screen throughout the experiment. Apart from describing each task, the instructions were also intended to prevent a strategy of waiting for tones and reacting to them, which participants might adopt spontaneously when IOIs are long but which was considered inappropriate in a synchronization task (see Repp & Doggett, 2007, for discussion).

> *Condition IP:* Tap in synchrony with each tone, to the best of your ability. DO NOT SUBDIVIDE intervals in any way (either mentally or by moving). Just let the time pass. Always try to PREDICT the next tone with your tap. Do NOT simply wait for the next tone and react to it. Of course, your tap will sometimes be too early and sometimes be too late, and if it is very late, you may find yourself reacting to the tone. However, do NOT adopt reacting as a deliberate strategy. (This applies to other conditions as well.) Start tapping with the third tone.
>
> *Condition MS:* Tap in synchrony with each tone, but SUBDIVIDE each interval MENTALLY (NOT by explicitly moving in any way) into TWO parts by IMAGINING either a sound or a movement at each interval midpoint. Start tapping with the third tone.
> *Condition DT:* Tap in synchrony with each tone AND at the midpoint of each interval. In other words, tap TWICE AS FAST as the sequence, such that every other tap coincides with a tone. Start tapping with the third tone.
>
> *Condition AP:* Tap ONLY at the midpoint of each interval, so that your tap divides the interval into halves. Start tapping after the third tone.

The author went over these instructions carefully with each participant before starting each session. Given that participants started tapping either on (IP, MS, DT) or right after (AP) the third tone, they made 29 taps per trial in conditions IP and MS, 57 taps (29 IP taps and 28 AP taps) in condition DT, and 28 taps in condition AP. The last IP tap followed the end of the pacing sequence.

ANALYSIS

In conditions IP and MS, and for the IP (odd-numbered) taps in condition DT, asynchronies between each tap and

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[3] An IOI duration of 3.5 s was intended to be included (as in Repp & Doggett, 2007) but did not materialize due to an undetected programming error; instead, each block was found to have an extra trial with the same IOI as the preceding one. These extra data were discarded.

the nearest tone were computed such that a negative asynchrony indicates that the tap was ahead of the tone. In condition AP, and for the AP (even-numbered) taps in condition DT, virtual asynchronies between taps and IOI midpoints were computed. A previously measured electronic processing delay of 15 ms for tap registration plus tone production was subtracted from all asynchronies. The asynchronies of the first two taps in each trial were omitted from analysis, but the virtual asynchrony of the final IP tap (relative to a time point extrapolated from the pacing sequence) was included. Intertap intervals (ITIs) were computed as well, with the first two ITIs being omitted from analysis. For condition DT, there were two sets of ITIs, one between IP taps and the other between AP taps. (The short ITIs between successive taps in that condition were not analyzed.) The raw data were examined to remove stray values due to occasional missing taps, extra taps, or apparent inattention of participants. The data points lost in that way amounted to 0.2% of all data, and ranged from 0 to 1% for individual participants. Means and standard deviations of asynchronies and of ITIs were then calculated.

Furthermore, as a measure of serial dependency that is potentially informative about differences in timing control between conditions, the lag-1 autocorrelation of each time series was calculated. (Missing data points were treated as blanks.) In addition, separate correlations were computed between the asynchronies for IP-AP and AP-IP successions of taps in condition DT, to investigate the hypothesis that AP taps, being the closest preceding events, serve as primary temporal references for IP taps, whereas preceding tones constitute the primary reference for IP taps. This hypothesis predicts larger AP-IP than IP-AP correlations.

All calculations were performed within trials and then averaged across blocks. The data were subjected to repeated-measures ANOVAs with the variables of tapping condition (4) and IOI duration (10). The data for the AP taps of condition DT were not included in these initial analyses. Additional ANOVAs were conducted as needed for specific comparisons. The Greenhouse-Geisser correction was applied to the *p* values whenever the number of levels of an effect exceeded two.

Results

MEAN ASYNCHRONIES AND INTERTAP INTERVALS

Mean asynchronies were negative at all IOIs, indicating that taps generally preceded tones, as is commonly found in studies of sensorimotor synchronization (Aschersleben, 2002; Repp, 2005). The ANOVA revealed only a significant main effect of IOI duration, $F(9, 54) = 7.89, p = .002$, due to a gradual increase of the negative mean asynchrony with IOI duration, from –25 ms to –57 ms.[4] This, too, is consistent with previous studies (e.g., Mates, Radil, Müller, & Pöppel, 1994; Repp, 2003). Mean ITIs (in condition DT, these were the intervals between either IP or AP taps) matched IOI durations closely because there were no instances of complete loss of synchrony (phase wrapping).

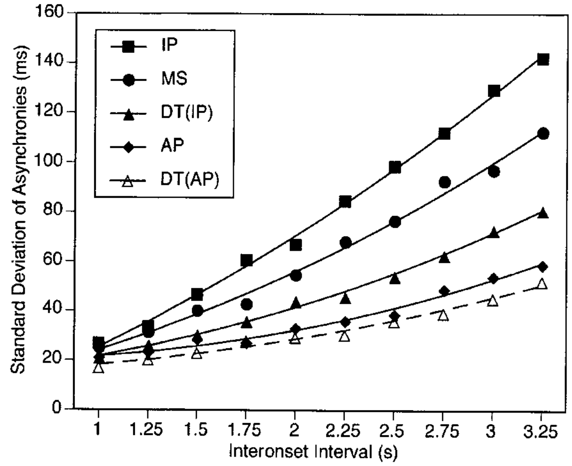

FIGURE 2. Mean standard deviation of asynchronies as a function of interonset interval duration in the four conditions, with separate data for IP and AP taps in condition DT. Quadratic functions have been fitted to the data.

VARIABILITY OF ASYNCHRONIES

Figure 2 shows the mean standard deviation of asynchronies in the four tapping conditions as a function of IOI duration. The data for IP and AP taps in the DT condition are shown separately and referred to as DT(IP) and DT(AP), respectively; at first, we consider only the DT(IP) taps. The ANOVA revealed highly significant main effects of tapping condition, $F(3, 18) = 48.75, p < .001$, and of IOI duration, $F(9, 54) = 112.55, p < .001$, as well as an interaction, $F(27, 162) = 15.27, p < .001$, because differences among the four conditions increased with IOI duration. Adjacent pairs of conditions were compared in additional ANOVAs. Variability was greater in

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[4] The mean asynchronies reported by Repp and Doggett (2007) in their Figure 1A for musicians' in-phase tapping without subdivision are too long by 15 ms because at the time of that study the electronic processing delay of the computer system was not known. If 15 ms are subtracted, the values are similar to those of the present mean asynchronies but show less of an increase with IOI duration.

IP than in MS, $F(1, 6) = 10.98, p = .016$, greater in MS than in DT(IP), $F(1, 6) = 44.81, p = .001$, and greater in DT(IP) than in AP, $F(1,6) = 51.07, p < .001$. Each of these differences also increased significantly with IOI duration: $F(9, 54) = 4.13, p = .045$, $F(9, 54) = 8.37, p = .001$, and $F(9, 54) = 7.51, p = .001$, respectively, for the interactions. The difference between the IP and MS condition showed considerable individual differences.

In each condition, the mean standard deviation increased almost linearly with IOI duration. Linear fits explain between 95.0% and 99.3% of the variance. Nevertheless, a slight upward curvature can be discerned in the functions. In the overall ANOVA, orthogonal polynomial decomposition of the main effect of IOI duration revealed, in addition to the obviously significant linear component, a significant quadratic trend, $F(1, 6) = 32.40$, $p = .001$, that, unlike the linear trend, did not differ among tapping conditions. Quadratic functions fitted to the data, as shown in Figure 2, account for 98.5% to 99.8% of the variance.

As can also be seen in Figure 2, differences among the conditions were nearly absent at the shortest IOI duration (1 s). Nevertheless, a one-way ANOVA on these specific data showed that the condition main effect was still significant, $F(3, 18) = 5.33, p = .033$. The convergence of the functions fitted to the data suggests that differences among the conditions might truly disappear around IOI = 0.9 s.

The virtual asynchronies of DT(AP) taps (open triangles in Figure 2) were significantly less variable than the asynchronies of DT(IP) taps, $F(1, 6) = 163.36, p < .001$, a remarkably consistent difference that increased with IOI duration, $F(9, 54) = 38.30, p < .001$. DT(AP) taps also were significantly less variable than the taps in condition AP, $F(1, 6) = 22.97, p = .003$. The interaction with IOI duration fell short of significance in that comparison.

VARIABILITY OF INTERTAP INTERVALS

The standard deviations of the ITIs, shown in Figure 3, were larger than those of the asynchronies but exhibited a similar pattern. Only the difference between conditions IP and MS fell short of significance, $F(1, 6) = 5.16, p = .064$, and the difference between DT(IP) and AP was also relatively small, $F(1, 6) = 11.59, p = .014$, whereas the difference between these pairs of conditions was very large. The functions also exhibited a significant quadratic trend, $F(1, 6) = 16.06, p = .007$. The variability of the intervals between DT(AP) taps was consistently smaller than that of the intervals between DT(IP) taps, $F(1, 6) = 103.71$, $p < .001$, and also significantly smaller than the variability of the ITIs in condition AP, $F(1, 6) = 39.52, p < .001$.

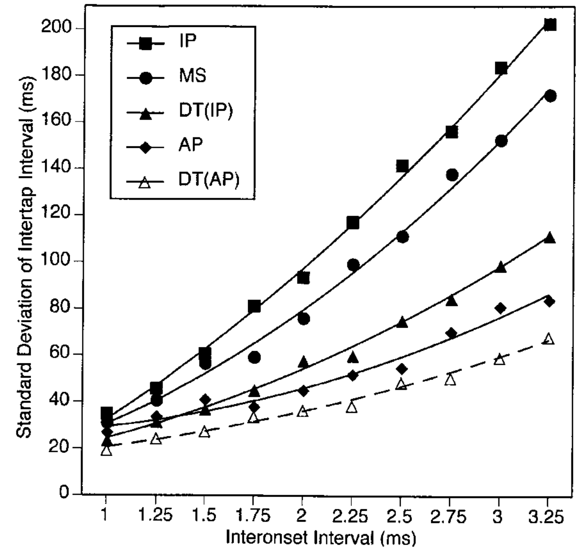

FIGURE 3. Mean standard deviation of intertap intervals as a function of interonset interval duration in the four conditions, with separate data for IP and AP taps in condition DT. Quadratic functions have been fitted to the data.

AUTOCORRELATIONS

Figure 4 shows the mean lag-1 autocorrelations (AC1 values) of the asynchronies. They decreased systematically as a function of IOI duration, from positive to zero or negative values, $F(9, 54) = 8.73, p = .004$. In addition to a linear trend, $F(1, 6) = 14.49, p = .009$, there was also

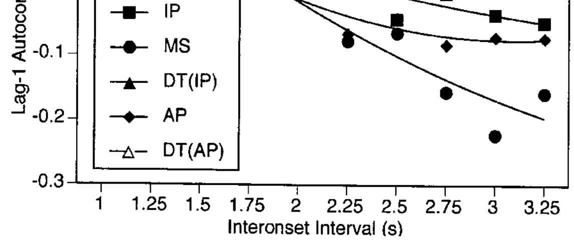

FIGURE 4. Mean lag-1 autocorrelations of asynchronies as a function of interonset interval duration in the four conditions, with separate data for IP and AP taps in condition DT. Quadratic functions have been fitted to the data.

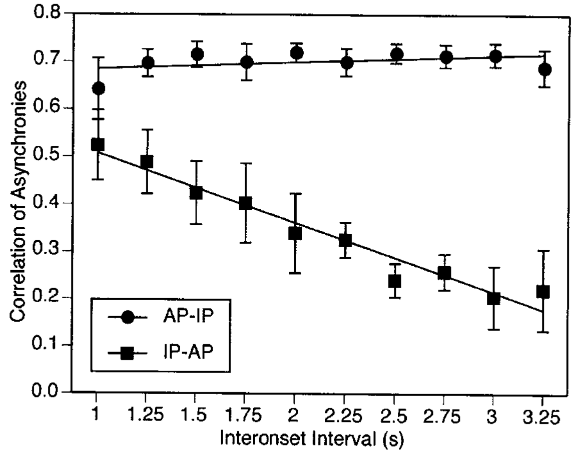

FIGURE 5. Mean correlations between asynchronies of successive taps in condition DT, with standard error bars. Linear functions have been fitted to the data.

a significant quadratic trend, *F*(1, 6) = 9.85, *p* = .020, which is why quadratic functions have been fitted to the data in the figure. Furthermore, there was also a significant main effect of tapping condition, *F*(3, 18) = 7.06, *p* = .009, which was mainly due to higher AC1 values for DT(IP) than for the other conditions; the effect was no longer significant when the DT(IP) condition was omitted from the ANOVA. Interactions with IOI duration were not significant. The AC1 values for DT(AP) asynchronies were even higher than those for DT(IP), *F*(1, 6) = 11.29, *p* = .015, and clearly higher than those in the AP condition, *F*(1, 6) = 12.67, *p* = .012, although there was considerable individual variability.

By contrast, the AC1 values for ITIs (not shown) did not vary significantly with either tapping condition or IOI duration. They were consistently negative, with a grand mean value of −.41.

One final result is shown in Figure 5. It concerns the serial dependency between IP and AP taps in the DT condition. The correlation between the asynchronies of successive AP and IP taps in Condition DT (labeled AP-IP in the figure) was large, positive, and essentially constant across IOI durations. By contrast, the correlation between the asynchronies of successive IP and AP taps (labeled IP-AP in the figure), while also positive, decreased steadily as IOI duration increased. This difference was highly reliable, both as a main effect, *F*(1, 6) = 95.07, *p* < .001, and as an interaction with IOI duration, *F*(9, 54) = 5.59, *p* < .001. The main effect of IOI duration was not significant. Separate ANOVAs confirmed that the AP-IP correlation did not change significantly with IOI duration, whereas the IP-AP correlation did, *F*(9, 54) = 4.54, *p* = .018, with only the linear component being significant. There were considerable individual differences in the IP-AP correlations, hence the relatively low significance level.

Discussion

The results for the IP and AP conditions replicate earlier findings of Repp and Doggett (2007); however, the difference in variability was even larger here, due to even lower variability in the AP condition. Thus, overt interval bisection clearly reduced variability. The negative mean asynchronies in the IP condition demonstrate that the participants followed instructions and did not adopt a strategy of waiting for and reacting to tones at long IOIs (Engström, Kelso, & Holroyd, 1996; Mates et al., 1994; Miyake, Onishi, & Pöppel, 2004), which arguably is not appropriate in a synchronization task (Repp & Doggett, 2007). To be sure, reactions to tones may have occurred occasionally when a tap would have been very late; in that case the tap may have been accelerated in response to the tone. Given a mean negative asynchrony (anticipation tendency), late taps were more likely at long IOI durations, due to increased variability of tap timing, and the resulting reactions (which shorten potentially long positive asynchronies) may have contributed to the increase in mean negative asynchrony with IOI duration. However, the mean asynchrony results do not confirm the finding of Wohlschläger and Koch (2000) that overt IOI subdivision (as in condition DT) decreases the negative mean asynchrony, as there was no difference among tapping conditions, perhaps because of the very long interval durations.

As hypothesized, mental subdivision (MS) by imagining a sound or movement at interval midpoints (as requested in the instructions) decreased the variability of asynchronies and also tended to decrease ITI variability, relative to the no-subdivision (IP) condition. Each participant showed such a MS benefit, but there were large individual differences in its size. Grondin and Killeen (2009) were surely correct when they suggested that musicians might have difficulty suppressing mental subdivision strategies. Some of the present participants were probably less successful than others in that endeavor. All participants acknowledged that it was difficult not to subdivide long IOIs. To the extent that they engaged in MS in the IP tapping condition, where subdivision was prohibited, the MS benefit would have been reduced. Nevertheless, there was a significant MS benefit overall. Although participants had been instructed not to move in the MS condition, slight, perhaps subconscious, movements are a natural concomitant of MS and may have contributed to the MS benefit.

Overt interval subdivision by tapping (conditions DT and AP) was clearly more effective than MS in reducing variability. Thus, making an actual movement and hearing an actual sound (a thud) improves timing precision more than does imagining a movement or a sound. It is possible that a silent movement would be less effective than a movement that is accompanied by sound, but this was not investigated here. Of course, movement and sound commonly occur together in music performance.

Grondin et al. (1999) found that subdivision by counting was beneficial only at interval durations longer than 1.2 s. There are many methodological differences between their study and the present one, but the fact that the present subdivision benefits were quite small at IOI durations of 1 s and 1.25 s can be seen as broadly consistent with their results. The present results suggest a definite limit to subdivision benefits around 0.9 s. Thus, there is not much to be gained from subdividing intervals in the range of typical musical beats (i.e., below 1 s). What helps is to divide longer intervals into beat-size intervals. Although only duple metrical subdivision (bisection) was investigated here, triple or quadruple subdivision might offer additional benefits at long interval durations. One might predict, for example, that quadruple subdivision would generate benefits beyond those yielded by duple subdivision at IOI durations longer than about 1.8 s. This could be tested in future research.

Of the two overt subdivision conditions, AP tapping was more effective than DT tapping in reducing variability relative to IP tapping. However, this difference was apparent only when comparing DT(IP) taps to AP taps. The variability of DT(AP) taps was in fact even lower than that of AP taps, and much lower than that of DT(IP) taps. This finding can be explained by considering taps as "timed reactions" to sequence tones.[5] A timed reaction involves measuring an interval from a temporal reference (Pressing, 1999). In condition IP, the timed interval is similar in duration to the sequence IOI, but in condition AP and in the case of DT(AP) taps, it is only about half that duration because the tapping target is the IOI midpoint. The task can be described in terms of hierarchically nested timekeepers (Pressing, 1998; Vorberg & Wing, 1996). Therefore, the observed difference in variability simply reflects the well-known increase in variability with interval duration (Peters, 1989). Indeed, it can be seen in Figure 2 that the variability for IOIs of 2 s and 3 s in Condition AP was similar to the variability for IOIs of 1 s and 1.5 s, respectively, in Condition IP. However, taps may have more than one temporal reference (Large, Fink, & Kelso, 2002; Repp, 2008b). Figure 6 illustrates hypothetical temporal references for tap timing in all four tasks.

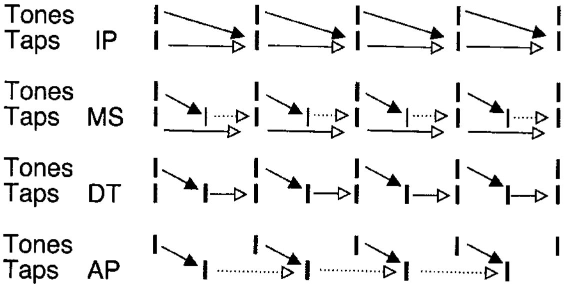

FIGURE 6. Hypothetical temporal references in the four synchronization tasks (IP, MS, DT, AP). Arrows with filled heads point from primary references to the timed event; arrows with open heads, from secondary references; arrows with dotted shafts, from tertiary references. A decrease in tempo will tend to increase the relative importance of the primary references and decrease especially the role of taps as references. All references should be understood to be internal representations of the external events.

The likely reason for the greater variability of DT(IP) taps than DT(AP) taps is that the former are timed primarily with reference to the temporally variable preceding DT(AP) tap,[6] whereas DT(AP) taps are referenced to the preceding tone of the metronome, which has no temporal variability apart from perceptual noise. This hypothesis finds strong support in the correlation data shown in Figure 5: The asynchronies of DT(IP) taps are highly correlated with those of the preceding DT(AP) taps at all IOI durations, whereas the asynchronies of DT(AP) taps depend less and less on those of the preceding DT(IP) taps as IOI duration increases. At short IOI durations, however, DT(IP) taps apparently served as (additional) temporal references for DT(AP) taps. It has been proposed previously that taps have dual temporal references (Hary & Moore, 1985, 1987; Repp, 2005), but recent data on phase correction in response

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[5] Timed reactions should not be confused with the previously mentioned immediate reactions to tones in the case of very late taps. Such immediate reactions are not explicitly timed.

[6] The temporal reference may be either the tactile and auditory feedback from the DT(AP) tap or a prediction of its time of occurrence, generated by an internal model, or some combination of prediction and feedback.

to perturbations (Repp, 2008c) have suggested that taps cease to serve as references for subsequent taps when IOIs exceed 1 s. However, the high positive AP-IP correlation observed here at 1 s and its very gradual decrease with IOI duration suggest that the temporal coherence of successive taps extends well beyond 1 s.

A finding that is more difficult to explain is the lower variability of DT(AP) taps than of the taps in Condition AP. It may reflect an additional contribution of the tapping period, which is half as long and hence less variable in condition DT than in condition AP. Because DT tapping is twice as fast as AP tapping, it is more continuous (less discrete) than AP tapping. Another way of describing this difference is that in DT tapping all ITIs are explicitly timed by an internal timekeeper that controls actions, whereas in AP tapping explicitly timed tone-tap intervals alternate with implicitly timed (i.e., merely perceived) tap-tone intervals (see Figure 6), because the taps do not serve as temporal references for action, or to a much lesser degree. Thus, there is less continuity in AP tapping than in DT tapping (in that connection, see also Mayville, Jantzen, Fuchs, Steinberg, & Kelso, 2002).

In all tapping conditions, variability of asynchronies and ITIs increased in a nearly linear fashion with IOI duration across the whole range from 1 to 3.25 s, which is consistent with a generalized form of Weber's law (Getty, 1975; Ivry & Hazeltine, 1995). However, there was an unexpected nonlinear component as well. This could be due to phase correction in synchronization, which contributes to variability. Not only does phase correction become more efficient as IOI duration increases (Repp, 2008c), but also the asynchronies become larger and hence more detectable, due to the increased timing variability. While phase correction at fast to moderate tapping rates is typically automatic and subconscious, at very slow tempi conscious correction of large errors is likely to play an increasing role, and overcorrection may occur. This may increase variability disproportionately. In condition AP, phase correction may be based on perception of inequality between the two halves of the bisected IOI, rather than on the virtual asynchrony between the tap and the IOI midpoint. Phase correction increases especially the variability of ITIs (Vorberg & Schulze, 2002), which is the likely reason why variability of ITIs was greater than variability of asynchronies at all IOIs. The rather large negative lag-1 autocorrelation of ITIs at all IOI durations is also likely to be a consequence of phase correction, which will tend to lead to alternating short and long ITIs.

The lag-1 autocorrelations of the asynchronies were positive at the shorter IOIs but decreased as IOI duration increased, reaching negative values in some conditions. Positive values (which tend to be even higher at IOIs of less than 1 s) are assumed to reflect fractal variability of an internal timekeeper or interval memory (Chen, Repp, & Patel, 2002; Delignières, Torre, & Lemoine, 2008; Torre & Delignières, 2008). Fractal variability is reflected in slow undulation (drift) of asynchronies, which results in positive autocorrelations. The decline of these autocorrelations with increasing IOI duration is likely due to increased phase correction, which tends to introduce alternating short and long values that break up the slow drift caused by internal timekeeper variability.

The fact that the standard deviation of ITIs increased almost linearly with IOI duration implies that the variance of ITIs increased nonlinearly with IOI duration. This explains why self-generated covert or overt subdivision of a long IOI reduces variability of ITIs: The sum of the variances of the two intervals generated by subdivision is smaller than the variance of the sum of the two intervals (cf. Getty, 1975, 1976), so that a subdivision benefit results unless there is a strong negative correlation between the two intervals. Because variability of asynchronies represents cumulative variability of subdivision intervals, at least in part (see Figure 6), the same argument explains why the variability of asynchronies is reduced by subdivision.

In summary, the present study demonstrates that a reduction of timing variability in synchronization can be achieved through covert or overt bisection of a long interval. Overt subdivision is more effective than covert subdivision, and a subdivision benefit begins to emerge only at intervals longer than about 1 s. The benefit increases steadily with interval duration, at least up to 3.25 s. The study also yielded useful psychophysical data, relevant to models of timing and synchronization, within a range of durations that has not been much investigated in the past. With regard to musical practice, it can be concluded tentatively that musicians probably will derive little benefit from subdivision of beat-size intervals, while their ensemble coordination may improve by subdivision of long intervals into beat-size units.

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