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Sensorimotor synchronization and perception of timing: Effects of music training and task experience

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ABSTRACT

To assess individual differences in basic synchronization skills and in perceptual sensitivity to timing deviations, brief tests made up of isochronous auditory sequences containing phase shifts or tempo changes were administered to 31 college students (most of them with little or no music training) and nine highly trained musicians (graduate students of music performance). Musicians showed smaller asynchronies, lower tapping variability, and greater perceptual sensitivity than college students, on average. They also showed faster phase correction following a tempo change in the pacing sequence. Unexpectedly, however, phase correction following a simple phase shift was unusually quick in both groups, especially in college students. It emerged that some of the musicians, who had previous experience with laboratory synchronization tasks, showed a much slower corrective response to phase shifts than did the other musicians. When these others were retested after having gained some task experience, their phase correction was slower than previously. These results show (1) that instantaneous phase correction in response to phase perturbations is more common than was previously believed, and suggest that (2) gradual phase correction is not a shortcoming but reflects a reduction in the strength of sensorimotor coupling afforded by practice.

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1. Introduction

Sensorimotor synchronization is a skill that is especially important for musicians when they have to play in ensembles. However, even people without music training are generally able to tap in

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approximate synchrony with a metronome or with the beat of music. Synchronization requires either continuous entrainment or discrete error correction, of which two forms – phase correction and period correction – have been identified in tapping tasks (Mates, 1994; Repp & Keller, 2004; for a review, see Repp (2005b)). *Phase correction* is the largely automatic adjustment of the timing of each tap on the basis of previous temporal information. *Period correction* in addition changes the internally specified period of the rhythmic action and seems to be more under cognitive control. Conscious detection of a tempo change in the pacing sequence may be necessary for period correction, or at least enhances it (Repp, 2001b; Repp & Keller, 2004), whereas phase correction is independent of conscious detection of timing perturbations or asynchronies (Repp, 2000, 2001a).

Both error correction processes have typically been found to be gradual, not instantaneous: When an unexpected timing perturbation is introduced into a pacing sequence during synchronization, participants usually need to make several taps to adapt fully to the change in timing. The shift of the first tap following a perturbation, relative to its expected time of occurrence, has been termed the *phase correction response* (PCR) and varies linearly with perturbation magnitude as long as the perturbations are relatively small. Thus the mean PCR can be expressed as a proportion of perturbation magnitude, and it is typically well below 1 unless the sequence tempo is very slow (Repp, 2008a, 2008b) or period correction accompanies phase correction (Repp & Keller, 2004). Other methods of estimating the speed of phase correction (e.g., Repp & Keller, 2008; Semjen, Schulze, & Vorberg, 2000) have likewise led to the conclusion that phase correction is rarely instantaneous, and period correction appears to be even slower (Repp, 2001b; Repp & Keller, 2004).

Previous studies from the author's laboratory have nearly always used musically trained individuals who were regular participants in synchronization tasks. A focus on such "synchronization experts" can be justified by the special relevance synchronization skills have to music performance and by a desire to obtain clean data from highly motivated participants. As a consequence, however, less is known about the synchronization skills of those with little or no music training. Although some studies by other researchers have used participants with little or (frequently) unspecified music training, comparisons across studies are difficult because of methodological differences, and a direct comparison of musicians' and nonmusicians' synchronization performance has rarely been made. It seems reasonable to expect that nonmusicians would exhibit larger asynchronies between taps and pacing sounds, greater tapping variability, and slower error correction than musicians. One recent study (Repp & Doggett, 2007) indeed found higher variability and a larger negative mean asynchrony (anticipation tendency) in nonmusicians than in musicians (see also Fran ek, Mates, Radil, Beck, & P oppel, 1991; G erard & Rosenfeld, 1995). However, effects of music training and/or of task experience on error correction processes have not yet been investigated directly.

The present study took advantage of a data set collected originally for a different purpose: to explore whether synchronization skills in college students are related to a measure of phonological fluency. That purpose will not be justified here; the results pertaining to it were modest and will be reported elsewhere, if at all. However, the availability of data from participants with (in most cases) little or no music training offered an opportunity to compare their synchronization performance to that of a small but readily available group of highly trained musicians in exactly the same tests. Some of these musicians had been regular participants in the author's research during the previous academic year, but most had just been recruited and thus were novices with regard to laboratory timing tasks, as were the college students. Thus, a comparison could be made that was largely unencumbered by possible effects of task experience. Such effects, if any, could be gauged by comparing the data for musicians with and without task experience, although the *N* was small. Within the group of college students, moreover, a comparison could be made between those without any music training and those with some training.

Three brief synchronization/perception tests were devised specifically for the purpose of assessing individual differences. The tests measured mean asynchronies and inter-tap intervals (ITIs), their variability, the speed of phase correction in response to phase shifts, the speed of phase and period correction in response to tempo changes, and also perceptual sensitivity to changes in timing and tempo. The hypothesis was simple: highly trained musicians were expected to be superior to less trained participants in all respects, and college students with music training were also expected to do better than those without any training. Possibly, musicians with extensive task experience would also do better

than those without. Better performance means smaller asynchronies, lower variability, faster error correction, and greater perceptual sensitivity. If all these predictions were confirmed, the results would not be particularly noteworthy, though perhaps useful for future reference. As will be seen, however, the error correction results were quite surprising and theoretically enlightening, and herein lies the interest of the present study.

2. Methods

2.1. Participants

2.1.1. Musicians

This group consisted of nine graduate students from the Yale School of Music (six women, ages 22–29). They had been trained on their primary instruments (piano-2, violin-2, viola, double bass, clarinet, bassoon, and harp) for 13–22 years. All had agreed to be paid participants in synchronization and perception experiments throughout the academic year. They had been selected from a larger group of graduate student volunteers, in part based on their performance in a screening test that assessed their “synchronization thresholds” for on-beat and off-beat tapping (see Repp, 2005a: Experiment 1). Six of them (“novices”) were tested in the first session following the screening in early fall; the other three (“veterans”) had been regular participants throughout the previous academic year and returned to the laboratory for the first time after the summer.

2.1.2. College students

These 31 participants (11 women) were recruited from the Introductory Psychology subject pool at the University of Connecticut and received course credit.¹ Eighteen participants (“nonmusicians”) had no music training at all, whereas the other 13 had 1–11 years of training on an instrument (“amateurs”). Only one amateur, the one with the longest training, still played actively (several wind instruments).

2.2. Materials

2.2.1. Phase correction test

Each sequence (trial) consisted of 10–14 high-pitched (E7, 2637 Hz) and hence rapidly decaying digital piano tones of unspecified duration. The baseline inter-onset interval (IOI) was 500 ms. A single phase shift, consisting of a shortening or lengthening of the preceding IOI, occurred four tones before the end. The magnitude of the phase shift ranged from –50 to 50 ms in increments of 10 ms, including zero. The combination of five sequence lengths and 11 phase shift magnitudes resulted in 55 trials that were presented in a fixed randomized sequence.

2.2.2. Tempo continuation test

This test served as a baseline condition for the subsequent period correction test and was intended to reveal any systematic biases in simple tempo continuation that should be taken into account in an assessment of period correction (Repp, 2001b). The IOIs were constant in each trial, with durations ranging from 450 to 550 ms in increments of 10 ms. Sequence length again ranged from 10–14 tones, resulting in 55 randomized trials.

2.2.3. Period correction test

This test was like the phase correction test, but a tempo change occurred instead of a phase shift. In other words, the last four sequence IOIs had a duration that differed from that of the preceding baseline IOIs (500 ms) by –50 to 50 ms in increments of 10 ms (durations of 450–550 ms). There were 55 randomized trials.

¹ The students' ages were not recorded but are likely to have been between 18 and 21 years. They had been selected according to good ($N = 15$) or poor ($N = 16$) performance on a pretest assessing phonological decoding ability (the Olson Pseudohomophone test; Olson, Forsberg, Wise, & Rack, 1994). These subgroups differed little in test performance and are combined here.

2.3. Equipment

Programs written in MAX 4.6.3 and running on a Macintosh computer controlled sequence presentation and data collection. Participants listened over earphones and tapped on a Roland SPD-6 electronic percussion pad. For the musicians, tested at Haskins Laboratories, the tones were produced by a Roland RD-250s digital piano connected to the computer via a MIDI interface. For the college students, tested at the University of Connecticut where a digital piano was not available, similar piano tones were generated via MIDI by the computer's downloadable sound (DLS) synthesizer. Acoustic measurements conducted at Haskins Laboratories have revealed electronic processing delays between finger-pad contact and contact-triggered sound onset of about 15 ms ($SD \sim 1$ ms) with the digital piano and 30 ms ($SD \sim 3$ ms) with audio output. These estimates were subtracted from the measured asynchronies.

2.4. Procedure

The tests were administered in the order in which they are described above. The phase correction and period correction tests were each preceded by four practice trials that illustrated trials without and with clearly audible (± 50 ms) timing perturbations. Participants were instructed to start tapping with the third tone they heard in each trial and to continue tapping in synchrony with the tones. In the phase correction test, they were to stop tapping when the auditory sequence ended and then press the down-arrow key on the computer keyboard if they had heard a temporal irregularity in the sequence, and the space bar otherwise. Either response started the next trial after a delay of 2 s. In the tempo continuation test, participants were to continue tapping at the same tempo after the sequence had ended, until they heard a single lower-pitched tone (the signal to stop tapping) that occurred 3.5 s after the last sequence tone. Then they pressed the space bar to start the next trial. In the period correction test, participants were to continue tapping at the *final* tempo of the sequence and, after hearing the signal to stop tapping, to press the down-arrow key if they had heard a tempo change in the sequence; the space bar otherwise.

3. Results

A summary of results is provided in Table 1 whose numbered rows will be referred to below (e.g., Table 1.3 refers to row 3).

3.1. Phase correction test

In all analyses of this test, one college student was omitted as an outlier because of an unusually small PCR slope (see below).

3.1.1. Asynchronies

Asynchronies were computed by subtracting the time of each tap from the time of the nearest tone as represented in the MAX software and were then corrected for electronic delays (see Section 2.3). Table 1.1 shows that the musicians had smaller mean asynchronies than the college students, $t(37) = 3.27$, $p = .002$, even though both groups showed the commonly observed tendency to tap in advance of the tones (i.e., negative means). However, there was no significant effect of music training within the college student group, nor was there a significant effect of task experience among the musicians.

The variability of asynchronies was determined within and between trials. The within-trial standard deviation (SD_w) was calculated across the three positions preceding the phase shift in each trial and then was averaged across all trials. The between-trial standard deviation (SD_b) was calculated across trials for each of the three positions preceding the phase shift and then averaged across positions. SD_b was generally larger than SD_w (Table 1.2 and 1.3). Musicians clearly tapped with less variability than did college students, $t(38) = 2.91$, $p = .006$, and $t(38) = 3.18$, $p = .003$, for SD_b and SD_w ,

Table 1

Summary of results, with standard errors of means. Signs of “<” or “>” indicate significant differences between adjacent values ($p < .05$). See text for detailed statistics and explanation of variables.

	Musicians			College Students		
	Veterans	Novices	All	All	Amateurs	Nonmusicians
<i>(A) Phase correction test</i>						
(1) Mean asy (ms)	−20.1 (4.9)	−28.9 (4.5)	−26.0 (3.5)	> −47.9 (3.3)	−46.4 (3.0)	−49.0 (5.6)
(2) Mean SD_b (ms)	13.0 (1.0)	14.6 (0.5)	14.1 (0.5)	< 29.7 (2.7)	29.0 (4.5)	30.3 (3.3)
(3) Mean SD_w (ms)	10.2 (0.3)	11.1 (0.7)	10.8 (0.5)	< 15.0 (0.6)	14.9 (1.0)	15.1 (0.7)
(4) Mean PCR slope	0.63 (0.09)	< 0.98 (0.04)	0.86 (0.07)	0.94 (0.05)	0.95 (0.07)	0.94 (0.06)
(5) Median R^2	.920	.877	.879	.863	.861	.866
(6) Mean d'	2.11 (0.12)	2.47 (0.15)	2.35 (0.12)	> 1.11 (0.14)	1.34 (0.19)	> 0.94 (0.19)
<i>(B) Tempo continuation test</i>						
(7) Mean slope	1.02 (0.04)	1.10 (0.03)	1.07 (0.02)	1.04 (0.02)	1.07 (0.03)	1.01 (0.03)
(8) Median R^2	.987	.987	.987	> .966	.966	.964
(9) Mean SD_c (ms)	16.0 (1.8)	16.0 (0.7)	16.0 (0.7)	< 18.9 (0.8)	17.8 (1.2)	19.8 (1.0)
(10) Mean SD_s (ms)	17.1 (0.6)	17.3 (0.8)	17.2 (0.6)	< 21.7 (0.7)	20.1 (1.1)	22.9 (0.9)
<i>(C) Period correction test</i>						
(11) Mean slope	1.11 (0.07)	1.09 (0.06)	1.10 (0.05)	1.00 (0.06)	0.97 (0.08)	1.03 (0.09)
(12) Median R^2	.980	.974	.980	> .913	.945	.896
(13) Mean d'	2.25 (0.21)	2.56 (0.20)	2.46 (0.15)	> 1.86 (0.11)	2.00 (0.16)	1.75 (0.14)

respectively. Again, neither task experience among the musicians nor music training among the college students had any effect.

3.1.2. Phase correction response

The PCR in each trial was calculated by subtracting the asynchrony at the phase shift from the following asynchrony.² To arrive at an estimate of the mean PCR based on data from all trials, PCRs were first averaged across trials with the same phase shift magnitude (excluding rare outliers larger than ± 150 ms) and then regressed onto phase shift magnitude, separately for each participant. The slope of the regression line (the PCR slope) expresses the mean PCR as a proportion of phase shift magnitude. The variance accounted for by the regression line (R^2) provides a measure of the linearity of the relationship and of variability in the PCR data. Strongly linear PCR functions have been obtained with similar tests in previous studies, with mean PCR slopes of .78 (Repp, 2002a: Experiment 6) or .64 (Repp, 2002b) for musically trained participants with task experience.

The mean PCR slope (Table 1.4) for the present group of musicians was a bit larger than expected on the basis of these previous data. The real surprise, however, was that the mean PCR slope of the college students was even larger, indicating almost instantaneous phase correction on average, although the group difference was not significant. (One college student was omitted as an outlier because of a mean PCR slope of only .18.) There was no effect of music training within the college student group. Within the musician group, however, a striking difference between veterans and novices was apparent, $t(7) = 3.91$, $p = .006$. The veterans showed a mean slope consistent with earlier findings (.63), whereas the novices showed instantaneous phase correction, on average (.98). It is worth adding that the author, who is a 10-years veteran of synchronization experiments and musically trained, though not as intensively as the musicians, also ran himself in the present tests and evinced a PCR slope of .37, even much shallower than the slopes of the three 1-year veterans. It appears that the PCR slope is related to task experience, not musical training, and decreases rather than increases with experience.

² As an example, suppose the phase shift is -50 ms, so that the first shifted tone occurs 50 ms sooner than expected. Then the tap synchronized with this tone is 50 ms late relative to the tone (assuming a mean asynchrony of zero and no variability, without loss of generality). Without any phase correction, the following tap would be 50 ms late, too, and the expected difference between the two asynchronies would be zero. The immediate effect of phase correction is to reduce the increment in the next asynchrony, and this reduction is the PCR. Because the reduction is achieved by shortening the preceding inter-tap interval (ITI) the PCR can also be calculated by subtracting the baseline IOI from the ITI following a phase shift.

Fig. 1 presents the mean PCR functions for the different subgroups. The median R^2 values (Table 1.5) indicate good linear fits in most individual cases, without any significant differences between groups or subgroups. However, whereas the mean functions for the musicians seem truly linear, those for the college students show a slight curvilinearity, which has been highlighted in Fig. 1B by fitting cubic rather than linear functions to these data. These PCR functions show a shallower slope near zero than at larger phase shift magnitudes, which unexpectedly suggests a role of conscious perception in phase correction. A two-way mixed-model ANOVA on the college student PCR data revealed a highly significant main effect of phase shift magnitude and no interaction with music training. Decomposition of the main effect into orthogonal polynomials revealed significant effects of linear ($p < .001$), quadratic ($p < .001$), cubic ($p = .001$), and quartic ($p = .035$) components, and for the cubic component there was also an interaction with music training, $F(1, 28) = 4.38, p = .046$, reflecting greater curvilinearity for nonmusicians than for amateurs. By contrast, a one-way ANOVA on the musicians' data with polynomial decomposition revealed only a highly significant linear trend.

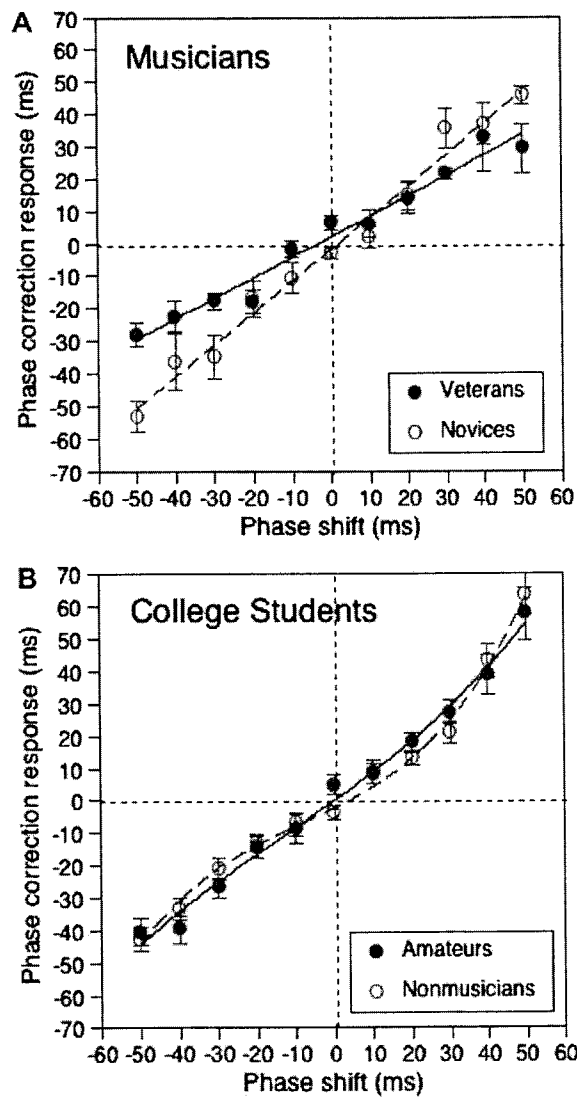


Fig. 1. Mean phase correction response as a function of phase shift magnitude for musicians differing in task experience (A) and college students with and without music training (B). Error bars are standard errors. Curve fits are linear (A) and cubic (B).

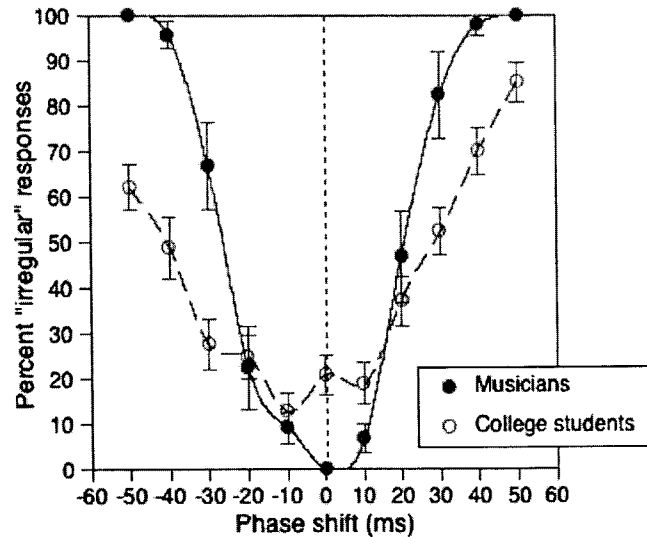


Fig. 2. Mean percentages of “irregular” responses as a function of phase shift magnitude for musicians and college students. Error bars are standard errors. Curve fits are splines.

3.1.3. Perception of phase shifts

At the end of each trial, participants reported whether the pacing sequence had been temporally regular or irregular. The mean percentages of “irregular” responses as a function of phase shift magnitude are shown for the two main participant groups in Fig. 2. It is clear that the musicians performed substantially better than the college students. They had both more hits (“irregular” responses when there was a phase shift) and fewer false alarms (“irregular” responses when there was no phase shift). College students found positive phase shifts (IOI lengthenings) easier to detect than negative phase shifts (IOI shortenings), and a similar but smaller asymmetry can also be seen in the musicians’ data.

To quantify these observations, a d' index of perceptual sensitivity (the difference between z-transformed hit and false alarm proportions) was computed for each participant. To obtain more reliable estimates of false alarm proportions (and indeed any estimate at all for musicians, who gave no false alarms), “irregular” responses to phase shifts of ± 10 ms ($\pm 2\%$ of the IOI), which are below the detection threshold of most listeners (Friberg & Sundberg, 1995), were considered false alarms and combined with responses to zero phase shifts. Separate d' indices were computed for negative and positive phase shifts (using the same false alarm proportion and averaging hit proportions across different phase shift magnitudes) and then averaged to obtain an overall index for each participant. The mean d' of the musicians (Table 1.6) was more than twice as large as that of the college students, $t(37) = 4.81$, $p < .001$. Musicians’ tendency to detect positive phase shifts (mean $d' = 2.54$) better than negative phase shifts (mean $d' = 2.17$) just fell short of significance, $t(8) = 2.29$, $p = .051$, but college students showed a highly reliable asymmetry (mean $d' = 1.43$ versus 0.80), $t(29) = 4.8$, $p < .001$. There was no significant effect of task experience among musicians. Among college students, musical amateurs did somewhat better than nonmusicians, $t(29) = 2.2$, $p = .05$.

3.2. Tempo continuation test

3.2.1. Continuation tempo

The purpose of this test was to assess any tendency to expand or compress tempo differences in continuation tapping, which sets a baseline for period correction in the subsequent test (cf. Repp, 2001b). Continuation tapping tempo was gauged by computing the mean duration of the three inter-tap intervals (ITIs) between the second and fifth continuation taps. After averaging across trials with the same IOI duration, the continuation ITI durations were regressed onto IOI duration for each participant, and the slope and R^2 of the regression line were recorded.

All participants showed a strongly linear relationship between IOI duration and continuation ITI duration, as can be seen in Fig. 3A. Unlike the musicians' mean regression line, however, the college students' mean regression line did not pass through the origin but had a y-axis intercept of about -10 ms, which (given a slope close to 1) means that their continuation tapping was too fast across the board. This group difference was significant, $F(1, 38) = 9.41, p = .004$. The mean regression slopes (Table 1.7) were slightly greater than 1, indicating slight exaggeration of the tempo differences during continuation tapping. There was no significant difference in slope between groups or subgroups, and no indication of any nonlinearity in the functions. However, the median R^2 values (Table 1.8) indicate better linear fits for the musicians than for the college students, evidently due to lower variability in the musicians' data; this difference was significant in a Mann-Whitney test, $z = 3.22, p = .001$.

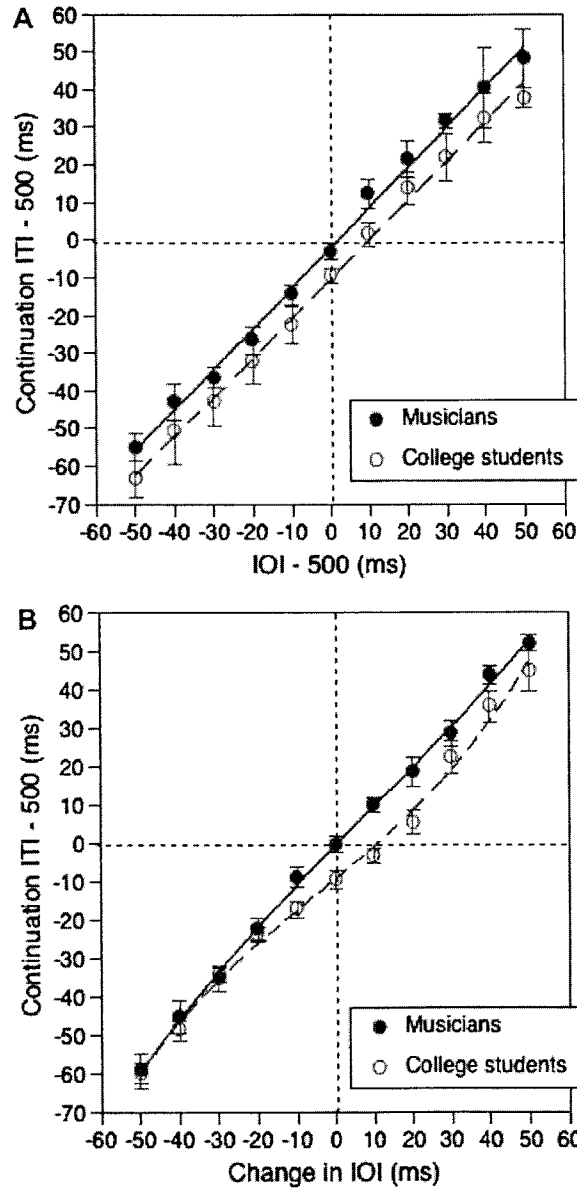


Fig. 3. Mean continuation inter-tap interval (ITI) duration as a function of sequence inter-onset interval (IOI) duration (both minus 500 ms) for musicians and college students in the tempo continuation test (A) and in the period correction test (B). Error bars are standard errors. Curve fits are linear (A) and cubic (B).

The standard deviation of the same three continuation ITIs was computed within each trial and then averaged across trials and IOI durations to obtain a grand mean index of variability (SD_c , Table 1.9). Musicians tapped with lower variability than did college students, $t(37) = 2.05$, $p < .047$. Another index of ITI variability was calculated from the last six ITIs during synchronization (SD_s , Table 1.10). That index, too, was lower for musicians than for college students, $t(37) = 3.22$, $p = .003$. SD_s was slightly larger than SD_c , as is commonly found (e.g., Semjen et al., 2000), because continuous phase correction during synchronization increases ITI variability. Musicians' task experience did not make a systematic difference. College student amateurs had somewhat lower variability than nonmusicians, but this difference was not significant.

3.3. Period correction test

3.3.1. Continuation tempo

In this test the tempo to be continued was exemplified only by the last four IOIs of the pacing sequence. The mean continuation ITI was computed in the same way as in the tempo continuation test. Again, both groups of participants showed a strong linear relationship of continuation ITI to final pacing IOI, as shown in Fig. 3B. However, one college student participant had a slope close to zero, despite showing normal data in the tempo continuation test. This participant was excluded as an outlier in all analyses of the current test. The mean slope (Table 1.11) for musicians was again a bit larger than 1, whereas it was exactly 1 for college students, not a significant difference. The perfect mean slope of the college students is a surprising finding, for on the basis of earlier research (Repp, 2001b; Repp & Keller, 2004) it had been expected that period correction would not yet be complete after four IOIs at the new tempo, especially in nonmusicians. However, the data indicate complete period correction, regardless of music training. The slopes in this test were not significantly smaller than those in the tempo continuation test. However, for college students the linear fits were poorer than in the tempo continuation test ($p < .01$, binomial test).

Fig. 3B shows that in contrast to the true linearity of their function in the tempo continuation test, the college students again showed some curvilinearity here, not unlike their function in the phase correction test (Fig. 1B). A two-way mixed-model ANOVA with orthogonal polynomial decomposition on the college student data revealed, besides a highly significant linear trend, significant cubic ($p = .002$) and quintic ($p = .002$) trends, but no interaction with music training. The shape of the curve is consistent with faster period correction when the tempo change is detected (Repp, 2001b). Polynomial

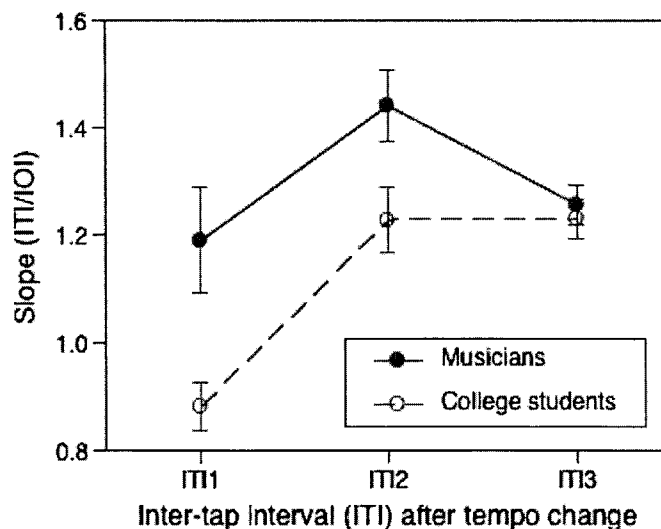


Fig. 4. Mean slope of the function relating ITI duration to IOI duration for each of the first three ITIs following a tempo change, for musicians and college students. Error bars are standard errors.

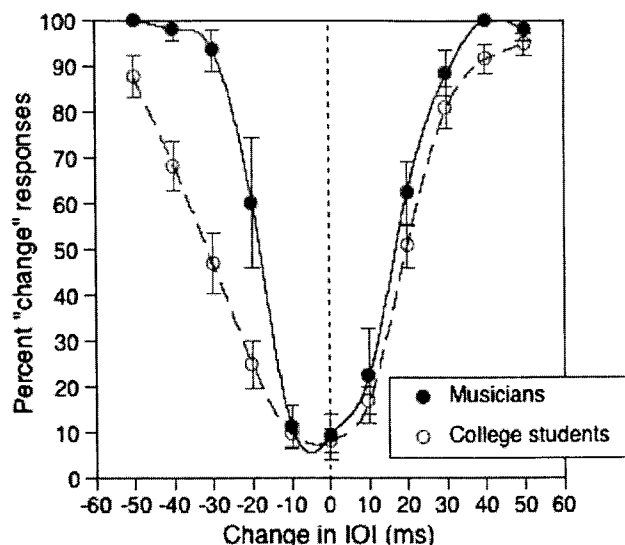


Fig. 5. Mean percentages of “change” responses as a function of IOI change magnitude for musicians and college students. Error bars are standard errors. Curve fits are splines.

decomposition of the musicians’ function did not reveal any significant deviation from linearity. As in the tempo continuation test, the college students’ regression line had a lower y-axis intercept than that of the musicians, but the difference did not reach significance here. The mean R^2 values of the linear fits (Table 1.12) were clearly higher for musicians than for college students, $z = 3.67$, $p < .001$ (Mann–Whitney test), which indicates less orderly data as well as deviations from linearity in the latter group.

3.3.2. Period and phase correction during synchronization

The continuation tempo results for the current test indicate that period correction was generally completed before the pacing sequence had ended. In order to adapt to a new tempo during synchronization, it is necessary to carry out both period correction and phase correction. The combined effect of these two corrections typically results in overcorrection; in other words, the slope of the regression line relating ITI to IOI duration is larger than 1. This overcorrection is not always evident in the first ITI following a tempo change and may emerge only in the second and/or third ITI (Repp & Keller, 2004). Therefore, the slopes of the regression lines relating the durations of the first, second, and third ITIs following the tempo change to IOI duration were determined. These slopes are shown in Fig. 4 for musicians and college students.

A two-way mixed-model ANOVA was conducted on these data. Musicians overcorrected more than did college students, $F(1, 38) = 5.25$, $p = .028$, and overcorrection increased from the first to the second (and third) ITI, $F(2, 76) = 17.14$, $p < .001$. The interaction was not significant, and differences within each group were not significant either. To correct completely for both the period change and the concomitant phase shift, the three slopes should add up to the number of intervals plus one.³ For musicians, this was nearly the case (sum = 3.86), whereas college students fell short of that goal

³ Suppose the IOI duration changes by -50 ms, from 500 to 450 ms. Thus, the tone terminating the changed IOI occurs 50 ms sooner than expected, and the tap synchronized with it occurs 50 ms late relative to the tone (again assuming a mean asynchrony of zero and no variability, without loss of generality). For the next tap to be in synchrony with the next tone, the preceding ITI would have to change by -100 ms because the next tone is shifted by -100 ms relative to where it would have occurred in the absence of a tempo change. Instantaneous phase and period correction would thus be reflected in a slope of 2 of the function relating ITI duration to IOI duration (or IOI change magnitude). If subsequently the new tempo is maintained, each ITI will equal the IOI and thus yield a function with a slope of 1. Therefore, the sum of slopes is equal to the number of ITIs plus 1 if both phase and period correction are complete.

(sum = 3.34). Because the tempo continuation data indicated that college students had corrected their period completely by the time they started continuation tapping (assuming there is no further period correction during continuation tapping; see Repp & Keller, 2004), it seems likely that this shortfall was due to inadequate phase correction following a tempo change.

3.3.3. Perception of tempo changes

After each trial, participants indicated whether or not they had detected a tempo change. The mean percentages of “change” responses as a function of IOI change magnitude are shown in Fig. 5 for musicians and college students. For both participant groups, detection of tempo changes was easier than detection of phase shifts (Fig. 2), as was fully expected (cf. Friberg & Sundberg, 1995). Discrimination indices (d') were calculated as previously, with “change” responses to tempo changes of ± 10 ms being counted as false alarms (Table 1.13). It is clear that musicians again performed better than college students in this temporal discrimination task, $t(37) = 2.80$, $p = .008$, and college students also did better with positive (mean $d' = 2.23$) than with negative (mean $d' = 1.50$) tempo changes, $t(29) = 6.60$, $p < .001$. In other words, they found a deceleration easier to detect than an acceleration, which may be related to their tendency to tap too fast when continuing the tempo. Musicians did not show such an asymmetry, regardless of task experience. College students' music training did not make a significant difference.

4. Discussion

4.1. Effects of music training

In several respects, the musicians clearly outperformed the college students as a group: they had smaller negative asynchronies, tapped with lower variability, and showed greater perceptual sensitivity to timing changes. These differences are not surprising, and similar differences have been demonstrated in previous studies (e.g., Ehrlé & Samson, 2005; Gérard & Rosenfeld, 1995; Repp, 1995; Repp & Doggett, 2007). Moreover, the present musicians were not only highly trained but also had been selected from among a larger sample of musician volunteers, mainly on the basis of their performance on a synchronization task (screening test). In other words, they were probably better than average in their synchronization skills even when compared to their peers. Furthermore, they were probably more strongly motivated than the college students. Although it seems likely that extensive musical training contributed to the musicians' good performance, a contribution of genetic predispositions that led them to become professional musicians cannot be ruled out.

The more limited musical training that the “amateurs” among the college students had received in the past had little influence on synchronization performance. However, amateurs performed better than nonmusicians with regard to detection of phase shifts. This difference may be related to the only indication of a difference in synchronization between these subgroups, namely the greater curvilinearity of the PCR function of the nonmusicians (Fig. 1B). The shape of this function suggests that phase correction was faster when phase shifts were detected than when they were not detected, a pattern that has not been observed previously in numerous studies with musically trained participants (e.g., Repp, 2000, 2001a, 2008b). One interpretation of such a pattern is that the college students augmented automatic phase correction with cognitively controlled period correction when they detected a phase shift. However, it is also possible that cognitive control can be exerted over phase correction (cf. Repp & Keller, 2008). In any case, the nonlinearity was relatively slight, and phase correction certainly did occur in response to phase shifts that were not consciously perceived, as demonstrated in previous studies (Repp, 2000, 2001a). This has been interpreted as evidence for phase resetting, with the preceding tone as the reference (Repp, 2005b).

Musicians did not exhibit nonlinearities in their PCR functions, in agreement with previous findings. Nor were their tempo continuation functions nonlinear in any way, even though one might have expected some nonlinearity given earlier findings with regard to period correction (Repp, 2001b; Repp & Keller, 2004). This was probably due to a ceiling effect: Period correction was simply complete when continuation tapping started. College students did exhibit a nonlinearity, however, consistent with an

influence of conscious detection of tempo change on period correction and suggesting that their period correction was not quite complete, despite the steep slope of their tempo continuation function. In any case, group comparisons with regard to period correction are hampered somewhat by the relative completeness of period correction.

The results of main interest concern phase correction. It was hypothesized that musicians would exhibit faster phase correction than college students. This prediction was confirmed only in the period correction test. It appears that the college students prioritized period correction and neglected phase correction in that task. In other words, they adopted a new tapping tempo but incurred larger asynchronies at the end of the pacing sequence. This is surprising only in view of their rapid phase correction in the phase correction test, and suggests strategic flexibility with regard to phase correction. Either the dual requirement of period and phase correction drew on common but insufficient processing resources, or the college students intentionally reduced their phase correction because they thought it was not important in this task. That phase correction can be reduced intentionally has been demonstrated in previous studies (Repp, 2002a, 2002b; Repp & Keller, 2004).

The prediction that phase correction would be faster in musicians than in college students was definitely not confirmed in the phase correction test. Not only was phase correction equally fast in the two groups (especially if the “veterans” among the musicians are left out of the picture for the moment) but it was basically instantaneous, at least on average. Instantaneous phase correction has rarely, if ever, been observed in previous studies with pacing sequences whose IOIs are near 500 ms. Some of these earlier studies used tests extremely similar to the present phase correction test and also used musically trained participants, although they were less highly trained than the present musicians (Repp, 2002a, 2002b). Other studies differed somewhat in design but used highly comparable groups of musicians, including the present veterans (Repp, 2008b) and even the identical group of musicians (recent, still unpublished work). None of these studies found PCRs close to 1. Therefore, the present findings are quite novel and still somewhat mysterious. However, they certainly provide an existence proof of instantaneous phase correction in both musicians and nonmusicians.

The finding has theoretical implications. The slope of the PCR function is a measure of the strength of sensorimotor coupling. It has been proposed that phase correction is controlled by two competing tendencies (Hary & Moore, 1985, 1987; Repp, 2005a, 2005b): (1) phase resetting in response to the preceding sequence tone and (2) maintenance of the tapping period, which inhibits phase resetting. Recently, Repp (2008b) equated the maintenance tendency with emergent timing, which is usually attributed only to continuous movements (Delignières, Torre, & Lemoine, 2008; Ivry, Spencer, Zelaznik, & Diedrichsen, 2002). Tapping is an activity whose timing is usually considered purely event-based, but a PCR slope of less than 1 may be interpreted as evidence for an additional emergent timing component in synchronization that inhibits phase resetting. Repp (2008b) showed that the mean PCR slope of a group of musicians (with task experience) increased steadily as the tempo of the pacing sequence decreased, reaching 1 at a period of about 1.1 s. This disappearance of the emergent timing component was attributed to the increased discreteness and variability of widely separated taps, which made the emergent timing component vanish. In the present study, however, there was no evidence of emergent timing in the majority of participants, both musicians and nonmusicians. If this result had been obtained only for college students, it could have been attributed to the greater variability of their taps. The “novice” musicians, however, had low tapping variability and yet showed instantaneous phase correction. This shows, at the very least, that emergent timing is not a necessary component of tapping at a rate of 2 Hz, and possibly that the two-component theory of timing is incorrect.

4.2. *Effects of task experience*

The most intriguing part of the present story, however, concerns possible effects of task experience on phase correction. Admittedly, these results are serendipitous and based on a very small sample of individuals, all musicians. However, the mean PCR slope values of the three veterans among the musicians were strikingly smaller than those of the six novices; there was no overlap. Moreover, the author showed an exceptionally small slope value. Indeed, he has long been aware of his slow

phase correction and has often wondered whether it might be due to his age (64 at the time of writing). It seems now that it may be due instead to his extensive task experience.

To test the hypothesis that the difference between veterans and novices was really due to task experience and not some other individual differences, all participants were retested about four months later. By that time, the novices were no longer novices, having performed a number of other synchronization tasks and perceptual experiments on a weekly basis. Of course, they were still less experienced than the veterans, but if task experience had an effect, they should have shown reduced PCR slopes on retesting. That was indeed the result for all six one-time novices. Their mean PCR slope was now 0.73 (SE = 0.06), significantly smaller than their previous mean slope of 0.98, $t(5) = 2.95$, $p = .032$. By contrast, the mean slope of the three veterans was similar to their previous mean value (0.65 versus 0.63). The author also reran himself and showed essentially the same slope as previously (0.35 versus 0.37). These results strongly support the hypothesis that task experience slows phase correction.

This result also has interesting theoretical implications. Contrary to what was initially assumed, faster phase correction is not necessarily better. One interpretation is that the emergent timing component comes only with practice and reflects increased automaticity of synchronization and a partial decoupling of tapping from the pacing sequence. This would imply that emergent timing does not reside in the tapping movement itself, which probably changes little with task experience (though this needs to be confirmed), but originates at a higher level of intentionality and strategic timing control. Zelaznik and Rosenbaum (submitted for publication) recently reached a similar conclusion after they had found that the timing of circle drawing, traditionally considered a paragon of emergent timing, became more like the timing of tapping when discrete auditory or tactile feedback was added. An alternative or additional possibility is that practiced participants simply become used to timing perturbations, pay less attention to them, and therefore react less strongly to them. In either case, however, the result is reduced variability of ITIs and greater autonomy of the rhythmic movement from the sensory input. The author's example shows that even with a PCR slope as low as 0.35, excellent synchronization can be maintained, as the variability of his asynchronies is consistently low.

Another possible implication of the present findings, however, is that estimates of the speed of phase correction obtained with a perturbation method may not be equivalent to estimates obtained by other methods. In inexperienced participants especially, the PCR slope may overestimate the speed of phase correction relative to estimates obtained with other methods. The PCR slope estimates the speed of phase correction in response to perturbations, whereas other methods estimate the speed of phase correction in the absence of perturbations (Vorberg & Schulze, 2002) or in the presence of continuous perturbations (Repp & Keller, 2008). These estimates may not be the same because of different task constraints and differential dependence on task experience. A comparison of different methods of estimating the speed of phase correction in the same individuals is overdue and planned for the near future.

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