Phase Correction in Sensorimotor Synchronization with Nonisochronous Sequences

Bruno H. Repp
Haskins Laboratories

Justin London
Carleton College

Peter E. Keller
Max Planck Institute for Human Cognitive and Brain Sciences, Leipzig, Germany

PHASE CORRECTION, WHICH IS NECESSARY for synchronization of movements with a rhythm, has been studied primarily with isochronous sequences. We used a phase perturbation method to examine phase correction in synchronization with nonisochronous sequences (3:2 interval ratios), using musically trained participants. In isochronous control sequences, the phase correction response (PCR) of the tap following a small phase shift was larger when the intervals were long (600 ms) than when they were short (400 ms). In nonisochronous cyclic two-interval patterns, we found a similar dependence of the PCR on the duration of the interval following a phase shift. In three-interval patterns, however, there was no clear dependence on interval duration. The metrical interpretation of the sequences (downbeat location) had no effect on phase correction. In general, phase correction was as effective with nonisochronous as with isochronous sequences.

Received January 10, 2008, accepted June 18, 2008.

Key words: synchronization, rhythm, tapping, phase correction, anisochrony

WHEN A MOVEMENT MUST BE SYNCHRONIZED with a rhythm, as in dancing or tapping with the beat of music, *phase correction* is necessary for the maintenance of synchrony (Vorberg & Wing, 1996). Phase correction has been studied extensively in synchronization of finger taps with isochronous sequences (see Repp, 2005). A few studies (e.g., Large, Fink, & Kelso, 2002; Repp, 2008a) have used more complex metrical sequences, but the taps were isochronous. In the present study, we investigated phase correction in synchronization with nonisochronous metrical sequences, which entailed nonisochronous tapping.

One way of assessing the effectiveness of phase correction is to introduce local phase perturbations in the sequence and examine the response to them in subsequent taps, averaging across a number of trials to reduce noise in the data (e.g., Repp, 2001, 2002). It is often sufficient to consider just the *phase correction response (PCR)* of the first tap following a perturbation. The PCR (a phase shift of the tap in the same direction as the perturbation) is largely automatic and occurs without the participant's awareness.

It is known that the PCR increases with interval duration in synchronization with isochronous sequences (Repp, 2008a, 2008b; Semjen, Schulze, & Vorberg, 2000). Therefore, we hypothesized that in synchronization with nonisochronous sequences the PCR will be larger following a long interval than following a short interval (cf. Semjen & Ivry, 2001). In addition, phase correction might be generally less effective with nonisochronous sequences because they are less familiar and more complex than isochronous sequences, which poses problems for both perception and production (e.g., Hannon & Trehub, 2005; Povel, 1981; Semjen & Ivry, 2001). Finally, we were interested in any effects of metrical interpretation: Would a larger PCR be obtained when a downbeat is perturbed than when a weak beat is perturbed? Previous studies have shown little effect of metrical interpretation on interval production in nonisochronous rhythms (Repp, London, & Keller, 2005; Snyder, Hannon, Large, & Christiansen, 2006), but this does not rule out a possible effect on phase correction.

Method

Nine graduate students from the Yale School of Music (ages 22-28) were paid to participate. In addition, author BHR (age 62), a life-long amateur pianist, participated.

Materials included two isochronous (2+2, 3+3), two nonisochronous two-interval (2+3, 3+2), and six

Music Perception VOLUME 26, ISSUE 2, PP. 171–175, ISSN 0730-7829, ELECTRONIC ISSN 1533-8312 DOI:10.1525/MP.2008.26.2.171

nonisochronous three-interval (2+2+3, 2+3+2, 3+2+2; 3+3+2, 3+2+3, 2+3+3) patterns. The interval durations were 400 ms ("2") and 600 ms ("3"). Each sequence consisted of 24 pattern cycles, articulated by digital piano tones (B-flat$_4$, 466 Hz) with a nominal duration of 50 ms. To induce the desired metrical interpretation (downbeat location), each sequence was preceded by a simple induction melody (composed by author JL). Each melody was isochronous at the basic pulse rate (200 ms) and comprised 8 measures. It articulated the metrical beat pattern through changes in pitch on each beat and repeating that pitch until the next beat.

The phase shifts introduced into these sequences (changes of single interval durations, appropriately spaced apart) had six magnitudes: −50, −30, −10, 10, 30, and 50 ms. Magnitude was constant within each sequence. The number of sequences for each interval pattern was 12 (isochronous), 24 (two intervals), or 18 (three intervals), in the course of which the interval preceding each tone in each pattern was perturbed 5, 10, and 9 times, respectively, at each magnitude. The sequences for each pattern were arranged in random order and preceded by a practice sequence not containing any perturbations. The 2 + 2 and 3 + 3 sequences were randomized together and preceded by two practice sequences, one for each sequence type.

A program written in MAX 4.6.3 controlled the experiment. The tones were produced on a Roland RD-250s digital piano and heard over Sennheiser HD540 II headphones. Participants tapped on the top left and top right segments of a Roland SPD-6 electronic percussion pad.

The experiment required three 1-hour sessions, typically 1 week apart, respectively for two-interval patterns, three-interval patterns containing two short intervals, and three-interval patterns containing two long intervals. The order of patterns (trial blocks) within each session was roughly counterbalanced across participants.

Participants pressed the space bar of the computer keyboard to start each trial. They started tapping during the induction melody and kept tapping in synchrony with the tones until the sequence ended. Tapping was bimanual, with the left hand tapping on each downbeat (to ensure secure adoption and maintenance of each metrical interpretation) and the right hand tapping on every beat. A musical notation of each rhythm, with downward and upward pointing note stems suggesting left and right hands, respectively, was shown to clarify the procedure and remained in view during the task.

Results

Only the data obtained from right-hand taps were analyzed. Mean asynchronies were computed for each tone in each pattern; the effects of perturbations were expected to cancel out. A 15-ms correction for electronic processing delays was made. To compute the mean PCR for each tone in each pattern, the asynchronies at all perturbation points and at the immediately following sequence positions were linearly regressed on perturbation magnitude. The difference between the two regression slopes is the mean PCR.

Asynchronies and Inter-tap Intervals

Figure 1A shows the mean asynchronies for the two-interval patterns. As expected on the basis of previous findings (e.g., Mates, Radil, Müller, & Pöppel, 1994; Repp, 2003), asynchronies were more negative in the slower isochronous sequence (3+3) than in the faster one (2+2), $F(1, 9) = 11.88$, $p = .007$. However, there was no effect of metrical strength, nor any interaction with pattern. For the nonisochronous two-interval patterns, there was likewise no main effect of metrical strength, nor was there any main effect of pattern. However, the interaction was significant, $F(1, 9) = 6.13$, $p = .035$. In each pattern, the mean asynchronies were more negative for the tone that was preceded by a short interval (contrary to isochronous patterns). This reflects an enhancement of the contrast between the short and long inter-tap intervals (ITIs), as observed in previous studies (Repp et al., 2005; Snyder et al., 2006). Compared to previous results, however, the present distortion was small. Overall, the mean asynchronies were also less negative in nonisochronous than in isochronous sequences, although that difference fell just short of significance in a joint ANOVA, $F(1, 9) = 5.05$, $p = .051$.

The mean asynchronies for the first set of three-interval patterns are shown in Figure 1B. A 3 × 3 ANOVA on these data revealed neither a main effect of metrical strength nor a main effect of pattern. However, the interaction was nearly significant, $F(4, 36) = 3.38$, $p = .051$, due especially to its quadratic component, $F(1, 9) = 11.28$, $p = .008$. Asynchronies were most negative for the second tone in the three-tone rhythmic group, least negative for the third tone, and intermediate for the first tone. This reflects a tendency to shorten the first short ITI and to lengthen the second short ITI. Such a tendency was also observed in our previous study (Repp et al., 2005).

Figure 1C shows the asynchronies for the second set of three-interval patterns. The ANOVA revealed no

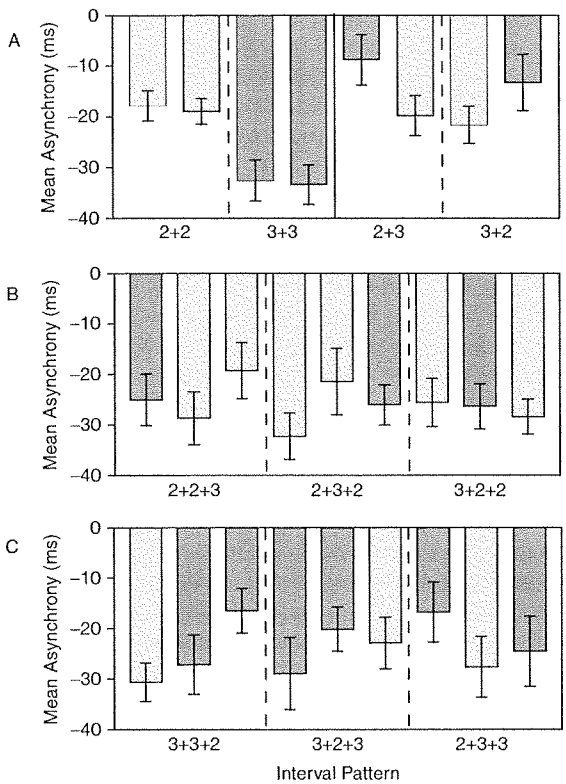

FIGURE 1. Mean asynchronies for each tone in (A) two-interval patterns, (B) three-interval patterns with two short intervals, and (C) three-interval patterns with two long intervals. The order of the bars corresponds to the order of tones within each pattern, with the first tone being the metrical downbeat. Dark bars represent tones *preceded* by long intervals; light bars, tones preceded by short intervals. Error bars are standard errors.

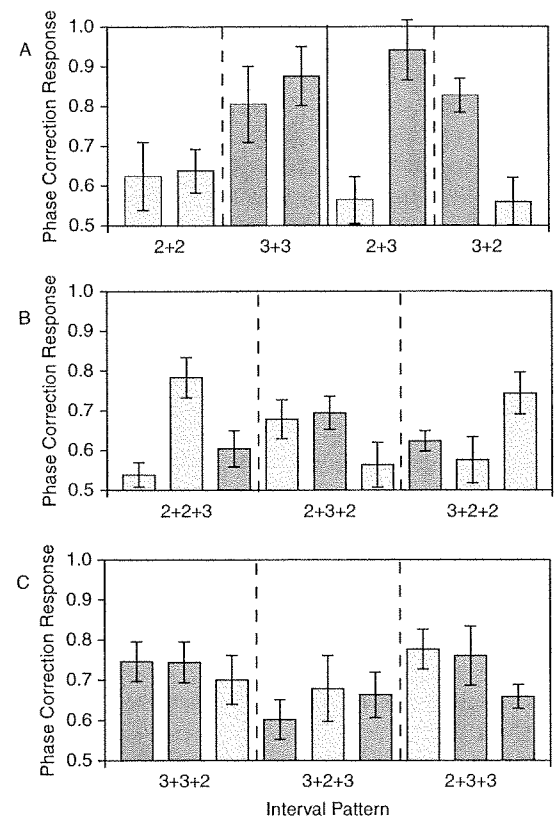

FIGURE 2. Mean phase correction response (PCR) for each perturbed tone in (A) two-interval patterns, (B) three-interval patterns with two short intervals, and (C) three-interval patterns with two long intervals. The order of the bars corresponds to the order of tones within each pattern, with the first tone being the metrical downbeat. Dark bars represent tones *followed* by long intervals; light bars, tones followed by short intervals. Error bars are standard errors.

main effects but a significant interaction, $F(4, 36) = 5.99$, $p = .003$. The asynchronies reflect a sharpening of the contrast between the short ITI and the preceding (but not the following) long ITI. The pattern shows some resemblance to that obtained in Repp et al. (2005).

Phase Correction Responses

Figure 2A shows the mean PCRs for the two-interval patterns. As predicted, the PCR was larger in slow (3+3) than in fast (2+2) isochronous sequences, $F(1, 9) = 19.93$, $p = .002$. There was no effect of metrical strength and no interaction. The PCRs for the 2+3 and 3+2 patterns showed a significant interaction, $F(1, 9) = 22.27$, $p = .001$, but no main effect of either metrical strength or pattern. The interaction implies an effect of rhythmic group position: The PCR was larger for perturbation of the second than of the first tone in the group. As in isochronous sequences, the PCR was larger when the interval following the perturbation was longer.

The PCRs for the three-interval patterns with two short intervals are shown in Figure 2B. Again there were no main effects, but the interaction was highly reliable, $F(4, 36) = 11.88$, $p < .001$, due mainly to its quadratic component, $F(1, 9) = 27.88$, $p = .001$. This again amounts to an effect of rhythmic group position: The PCR was smallest for perturbations of the first tone in the group and largest for perturbations of the second tone. However, because it is the third tone that is followed by a long IOI, this pattern is not consistent with an explanation based on IOI or ITI duration.

Finally, Figure 2C shows the PCRs for the three-interval patterns with two long intervals. Here there were no

significant effects. If IOI or ITI duration had been important, perturbation of the first tone in the two-tone group (the tone that comes first in 2+3+3) should have elicited the smallest PCR, but that was not the case.

Discussion

The asynchrony and ITI results are generally consistent with previous findings (Repp et al., 2005). The PCR results for isochronous sequences are also in agreement with earlier findings (e.g., Repp, 2008a, 2008b) showing that the PCR is larger at a slower tempo than at a faster tempo. This has been attributed to inhibition of phase resetting by a tendency to maintain the period of the tapping movement, a tendency that gets weaker as the period gets longer. The results for two-interval patterns suggest that this tendency generalizes to nonisochronous movements: The PCR was larger following a long interval than following a short interval. Yet, this finding is not quite consistent with the period maintenance hypothesis, which presupposes a periodic movement. It may be that the flexibility of movement timing depends on local interval duration and does not require strict periodicity.

Interestingly, however, this interval dependence of the PCR did not generalize to three-interval patterns. In patterns with two short intervals, there were significant differences in the magnitude of the PCR to perturbation of different tones in the cycle, but surprisingly the PCR was larger for the middle tone of the three-tone group than for the final tone (the one followed by a long interval). In the patterns with two long intervals, the PCR did not vary significantly for different tones. From these results, no consistent principle governing phase correction in nonisochronous patterns emerges.

Metrical interpretation had no effect on phase correction. This also indicates that making a tap on every downbeat with the left hand was irrelevant to the PCR. Even though the different patterns within each set must have been subjectively quite different, these subjective impressions evidently arose at a cognitive level of processing that is unconnected to the mechanisms of phase correction or, for that matter, to the timing of the taps in the absence of any perturbations (cf. Repp et al., 2005).

The results suggest that phase correction is about as effective with nonisochronous metrical sequences as with isochronous ones, at least for musically trained participants. It remains to be seen whether this result will hold up for sequences that have more complex (nonmetrical) interval ratios. However, we predict that as long as synchronization can be achieved, phase correction will be operating normally and continuously. In conclusion, our results suggest that the basic error correction mechanisms that enable humans to synchronize with a simple beat also underlie synchronization of movements with complex musical rhythms.

Author Note

This research was supported by National Science Foundation grant BCS-0642506 to BHR and by grant H01F-00729 from the Polish Ministry of Science and Higher Education to PEK.

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

References

HANNON, E. E., & TREHUB, S. E. (2005). Metrical categories in infancy and adulthood. *Psychological Science, 16,* 48-55.

LARGE, E. W., FINK, P., & KELSO, J. A. S. (2002). Tracking simple and complex sequences. *Psychological Research, 66,* 3-17.

MATES, J., RADIL, T., MÜLLER, U., & PÖPPEL, E. (1994). Temporal integration in sensorimotor synchronization. *Journal of Cognitive Neuroscience, 6,* 332-340.

POVEL, D.-J. (1981). Internal representation of simple temporal patterns. *Journal of Experimental Psychology: Human Perception and Performance, 7,* 3-18.

REPP, B. H. (2001). Phase correction, phase resetting, and phase shifts after subliminal timing perturbations in sensorimotor synchronization. *Journal of Experimental Psychology: Human Perception and Performance, 27,* 600-621.

REPP, B. H. (2002). Automaticity and voluntary control of phase correction following event onset shifts in sensorimotor synchronization. *Journal of Experimental Psychology: Human Perception and Performance, 28,* 410-430.

REPP, B. H. (2003). Rate limits in sensorimotor synchronization with auditory and visual sequences: The synchronization threshold and the benefits and costs of interval subdivision. *Journal of Motor Behavior, 35,* 355-370.

REPP, B. H. (2005). Sensorimotor synchronization: A review of the tapping literature. *Psychonomic Bulletin and Review, 12,* 969-992.

REPP, B. H. (2008a). Multiple temporal references in sensorimotor synchronization with metrical auditory sequences. *Psychological Research, 72,* 79-98.

REPP, B. H. (2008b). Perfect phase correction in synchronization with slow auditory sequences. *Journal of Motor Behavior, 40,* 363-367.

REPP, B. H., LONDON, J., & KELLER, P. E. (2005). Production and synchronization of uneven rhythms at fast tempi. *Music Perception, 23,* 61-78.

SEMJEN, A., & IVRY, R. B. (2001). The coupled oscillator model of between-hand coordination in alternate-hand tapping: A reappraisal. *Journal of Experimental Psychology: Human Perception and Performance, 27,* 251-265.

SEMJEN, A., SCHULZE, H.-H., & VORBERG, D. (2000). Timing precision in continuation and synchronization tapping. *Psychological Research, 63,* 137-147.

SNYDER, J. S., HANNON, E. E., LARGE, E. W., & CHRISTIANSEN, M. H. (2006). Synchronization and continuation tapping to complex meters. *Music Perception, 24,* 135-146.

VORBERG, D., & WING, A. (1996). Modeling variability and dependence in timing. In H. Heuer & S. W. Keele (Eds.), *Handbook of perception and action, Vol. 2* (pp. 181-262). London: Academic Press.