

Perfect Phase Correction in Synchronization With Slow Auditory Sequences

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ABSTRACT. Phase correction during synchronization (finger tapping) with an isochronous auditory sequence is typically imperfect, requiring several taps to complete. However, two independent hypotheses predict that phase correction should approach perfection when the sequence tempo is slow. The present results confirm this prediction. The experiment used a phase perturbation method and a group of musically trained participants. As the sequence interonset interval increased from 300 to 1200 ms, the phase correction response to perturbations increased and approached instantaneous phase resetting between 700 and 1200 ms, depending on the individual. A possible explanation of this finding is that emergent timing of the periodic finger movement vanishes as the movement frequency decreases and thus ceases to compete with event-based timing.

Keywords: phase correction, synchronization, tapping, tempo

Phase correction is necessary to maintain synchrony between a periodic movement and an externally controlled rhythm. Researchers have studied this process most often in finger tapping with isochronous (or nearly isochronous) auditory sequences. Phase correction is well explained by a linear model according to which the timing of each tap is adjusted by a fixed proportion of the preceding asynchrony. That proportion, the phase correction parameter α , can be estimated from the time series of asynchronies (Vorberg & Schulze, 2002). Alternatively, a perturbation method can be used: The researcher introduces small phase perturbations of various magnitudes in an isochronous sequence and measures the *phase correction response* (PCR) of the tap immediately after each perturbation (i.e., the shift of the tap from its expected temporal position). The slope of the regression line relating the PCR to perturbation magnitude then provides an estimate of α (Repp, 2002a).

Although phase correction is largely an automatic process, it can nevertheless be influenced by a variety of factors, such as instructions (Repp, 2002b), experimental context (Repp, 2002c), task difficulty (Repp & Keller, 2008), and sequence tempo (Repp, 2008). An α value of 1 indicates perfect phase correction or instantaneous phase resetting. α can reach 1 under certain conditions but is typically much smaller, with values around .5 often being reported. This raises the question: Why is phase correction usually imperfect?

Researchers have proposed two explanations. Vorberg and Schulze (2002) demonstrated mathematically that the variance of the asynchronies is minimal at a certain value of $\alpha < 1$. Following Wing and Kristofferson (1973a, 1973b), Vorberg and Schulze assumed two variance components,

one arising from an internal timekeeper, and the other arising from motor implementation delays. The *optimal* α depends on the ratio of these two variance components, being larger when the motor variance is relatively small. If participants' goal is variance minimization—and this is not an unreasonable assumption—then their α should be close to the optimal value. However, obtained α values are typically much smaller (e.g., Semjen, Schulze, & Vorberg, 2000), suggesting that variance minimization is not a complete account of why phase correction is imperfect.

I have proposed a different explanation (Repp, 2001). It is a variant of the idea of mixed phase resetting (Hary & Moore, 1985, 1987), according to which each tap is timed from either the preceding sequence event (event-based phase resetting) or from the preceding tap (tap-based phase resetting). Rather than assuming, as Hary and Moore (1985, 1987) have done, that these two resetting processes alternate randomly from tap to tap, I suggested that these two processes are in dynamic competition. The event-based resetting process is a form of explicit or discrete timing, governed by an internal timekeeper or interval memory. The tap-based resetting process can be regarded as a form of implicit or emergent timing (Zelaznik, Spencer, & Ivry, 2002), which implies a tendency to maintain the period of a repetitive motor activity (cf. the "maintenance tendency" of von Holst, 1939/1973). Although Zelaznik et al. focused on tapping as an example of purely event-based timing, I am claiming here that there is an emergent timing component in tapping as well. According to this hypothesis, emergent timing competes with discrete timing and prevents perfect (event-based) phase resetting.

My hypothesis has received considerable empirical support so far (see Repp, 2005, for a review). For example, phase correction does tend to be perfect (or even to deviate in the direction of overcorrection) when the tap coinciding with a phase perturbation is omitted or when tapping only starts after the perturbation (Repp, 2001). According to my hypothesis, the interruption or absence of continuous motor activity removes the maintenance tendency and the inhibition it exerts on phase correction.

Both hypotheses (variance minimization and competing timing processes) predict that as the sequence tempo slows, α should increase and eventually reach 1. The variance

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minimization hypothesis makes this prediction because it is well known that timekeeper variance increases with interval duration, whereas motor variance remains nearly constant (Wing, 1980). As the ratio between these two variance components increases, the optimal α approaches 1. My hypothesis of competing timing processes makes the same prediction because the emergent timing of the motor activity is assumed to be strongest when the period is short and the tapping movement is more nearly oscillatory. Slowing the movement will make it more discrete and will eventually eliminate the maintenance tendency, thereby releasing phase correction from inhibition.

A few previous studies have shown that α increases when the sequence tempo slows. However, these studies have used limited ranges of interonset interval (IOI) durations. Semjen et al. (2000) used IOIs ranging from 200 to 640 ms with musically trained participants and found that α (estimated from time series) increased steadily from very low values to about 0.5. Repp, London, and Keller (2007) used just two IOI durations, 400 and 600 ms, as control conditions in a perturbation study with highly trained musicians (the same participants as in the present study) and found α values of about 0.6 and 0.8, respectively. Repp (2008) used two IOI durations, 540 and 720 ms, with musically trained participants who were cued to omit the taps that coincided with perturbations. The mean α s were 0.8 and about 1.05, respectively. Thus, although the motor activity was disrupted, there seemed to be a residual maintenance tendency at the faster tempo. Other studies in the literature have used a wider range of tempo conditions (e.g., Mates, Radil, Müller, & Pöppel, 1994; Repp & Doggett, 2007), but they did not report estimates of α .

The purpose of the present study was to use the perturbation method to obtain estimates of α at IOIs ranging from 300 to 1200 ms. I expected that α would increase steadily and perhaps reach 1 within this range. Two types of perturbation were used, as illustrated in Figure 1A: *phase shift* (PS) and *event onset shift* (EOS). They differ in that a PS requires phase correction for maintenance of synchrony with subsequent tones, whereas an EOS does not. An EOS nevertheless elicits an automatic PCR, although it tends to be smaller than that of a PS if the researcher instructs participants to ignore the EOS (Repp, 2002a, 2002b). However, in the present study, I gave no such instructions, and so I expected the PCRs to PS and EOS perturbations (which are initially identical) to be similar.

Method

Participants

Participants were 7 paid volunteers and myself. The paid participants were all graduate students at the Yale School of Music (3 pianists, 3 clarinetists, and 1 harpist) who had agreed to serve in a series of experiments. Their ages ranged from 22 to 28 years, and they had studied their instruments for 13–24 years. I was 63 years old, a life-long amateur pianist, and highly experienced in synchronization tasks.

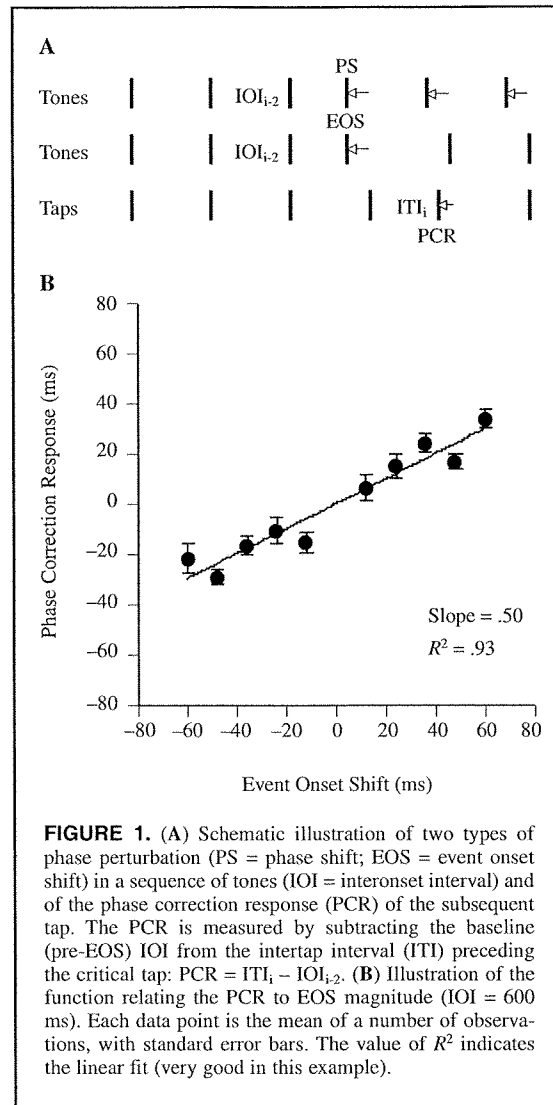


FIGURE 1. (A) Schematic illustration of two types of phase perturbation (PS = phase shift; EOS = event onset shift) in a sequence of tones (IOI = interonset interval) and of the phase correction response (PCR) of the subsequent tap. The PCR is measured by subtracting the baseline (pre-EOS) IOI from the intertap interval (ITI) preceding the critical tap: $PCR = ITI_i - IOI_{i-2}$. (B) Illustration of the function relating the PCR to EOS magnitude (IOI = 600 ms). Each data point is the mean of a number of observations, with standard error bars. The value of R^2 indicates the linear fit (very good in this example).

Materials and Equipment

Auditory sequences consisted of digital piano tones with a fundamental frequency of 261 Hz (C4) and a nominal duration of 40 ms. Sequences were generated online and comprised a variable number of tones. IOI was constant within each sequence and ranged from 300 to 1200 ms in increments of 100 ms. The resulting 10 sequences, randomly ordered, constituted one block of trials. Each sequence contained 11 phase perturbations whose magnitude ranged from -10% to 10% of the IOI in increments of 2%. (The "perturbation" of 0%, although nominally present, was ignored in the analyses.) Successive perturbations were separated by a variable number of tones that was randomly chosen from the range 5–8. The order of perturbation magnitudes within each sequence was random as well. The

perturbations were either of the PS type or of the EOS type; these were presented in separate sessions whose order was counterbalanced across participants. Each session consisted of five blocks of trials.

Programs written in MAX 4.6.3 and running on an Intel iMac computer (OS 10.4.10) controlled the experiment. The tones were produced on a Roland RD-250s digital piano that was connected to the computer via a MOTU Fastlane MIDI interface. Participants heard the tones over Sennheiser HD540 II headphones and tapped on a Roland SPD-6 electronic percussion pad that was likewise connected to the MIDI interface.

Procedure

I instructed participants to start each trial by pressing the space bar, to start tapping with the third tone that they heard, and to stay in synchrony with the tones. Participants were free to choose their most comfortable style of tapping. After each block of trials, they saved their data and initiated the next block. A trial could be repeated if anything went wrong, but this option was used rarely. Participants were told that there might be slight temporal irregularities in the sequences.

Results

I calculated the PCR to each perturbation by subtracting the baseline IOI (i.e., the predicted intertap interval) from the current intertap interval (see Figure 1A). I averaged the PCRs for each perturbation magnitude at each IOI duration across the five blocks of each session before regressing these means onto perturbation magnitude, as illustrated in Figure 1B. This was done separately for each IOI duration, perturbation type, and participant. Each regression line (PCR function) was thus based on 10 data points derived from 50 PCRs. Its slope provided an estimate of α . The value of R^2 (variance accounted for) served as an index of the goodness of fit of the PCR function. There were no indications of systematic deviations from linearity.

The results, averaged across participants, are shown in Figure 2. The upper panel shows the mean α estimates for the two perturbation types as a function of IOI duration. Linear regression lines have been fitted to these data. It is evident that α increased with IOI duration, as predicted, and that it reached 1 at the longest IOI durations. The main effect of IOI duration was highly significant in a repeated measures analysis of variance, $F(9, 63) = 23.40$, $p < .001$ (Greenhouse-Geisser corrected). Decomposition of the effect into orthogonal polynomial components revealed a highly significant linear effect, $F(1, 7) = 330.60$, $p < .001$, and a marginally significant sixth-order effect, $F(1, 7) = 5.84$, $p = .046$, which could have arisen by chance. Although α values tended to be higher for PS perturbations than for EOS perturbations, this difference was not significant, $F(1, 7) = 3.33$, $p = .111$. The interaction between type of perturbation and IOI duration was likewise nonsignificant, $F(9, 63) = 1.61$, $p = .205$. This indicates that the shapes of the PS and EOS functions were not systematically different.

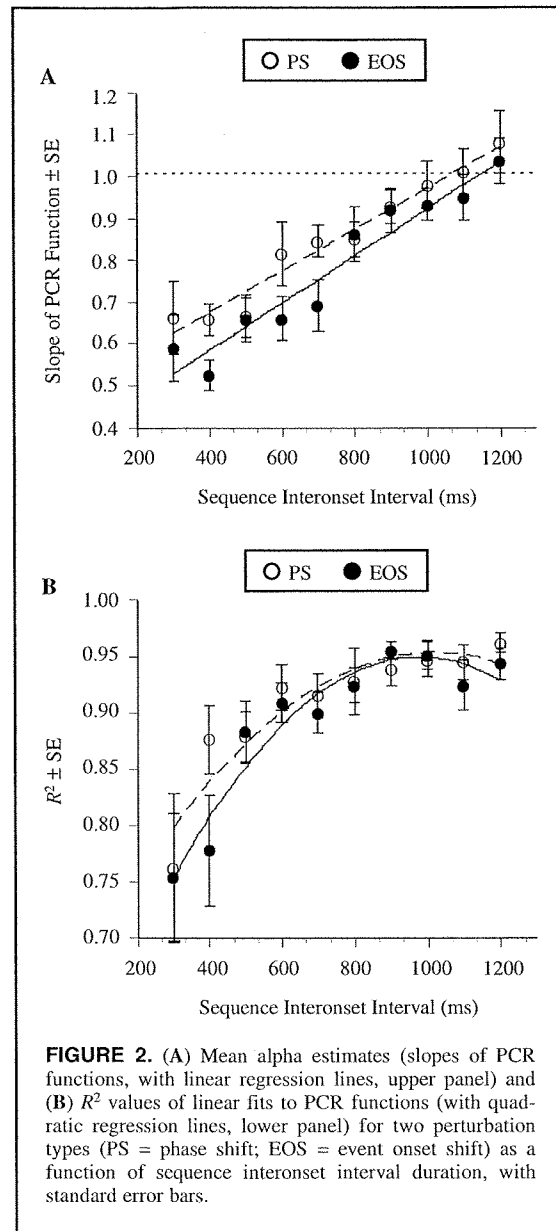


FIGURE 2. (A) Mean alpha estimates (slopes of PCR functions, with linear regression lines, upper panel) and (B) R^2 values of linear fits to PCR functions (with quadratic regression lines, lower panel) for two perturbation types (PS = phase shift; EOS = event onset shift) as a function of sequence interonset interval duration, with standard error bars.

The lower panel of Figure 2 shows the mean value of R^2 as a function of IOI duration, with quadratic functions fitted to the data. It is clear that the linear fits to the PCR functions were good at all but the shortest IOIs.

Although the increase in mean α with IOI duration was approximately linear, I must note that individual participants' functions deviated considerably from linearity. In all, one participant (whose performance in other experiments has indicated exceptional rhythmic acuity) showed perfect phase correction at the shortest IOI (300 ms), with a subsequent decrease in α before it increased again. This finding

was quite unexpected and remains unexplained. Another participant showed a similar but weaker nonmonotonicity at short IOI durations. Several participants achieved perfect phase correction sooner than Figure 2 indicates (i.e., at IOIs of 700–900 ms), whereas two participants never quite reached an α of 1. The results for myself showed a relatively low α at short IOIs but then a linear increase reaching 1 at the longest IOI (1200 ms). There were also some instances of overcorrection ($\alpha > 1$) at long IOI durations. The strong linear trend in mean α (Figure 2) likewise suggests the possibility of overcorrection at IOIs beyond 1200 ms, although neither hypothesis predicts this.

Discussion

Although the observed increase in α with IOI duration is not quite as smooth and regular as one might wish, it does confirm the qualitative predictions of the two aforementioned hypotheses. Actually, the variability minimization hypothesis makes quantitative predictions (if the variance components are known) but predicts higher α values than I actually obtained. For example, if the timekeeper variance is merely four times as large as the motor variance, a condition that holds only at very short IOIs, then the optimal α is already 0.83 (Vorberg & Schulze, 2002). When the IOI is 500 ms, the timekeeper variance is typically already more than 10 times as large as the motor variance (Wing, 1980), so phase correction should be nearly perfect at that tempo, but it is not. An additional explanation is necessary for why participants fall short of the optimal α values, and this weakens the variance minimization hypothesis. Therefore, I prefer the explanation that increases in IOI duration reduce the continuity of the tapping movements and thus remove the inhibition that the maintenance tendency exerts on event-based phase resetting. However, the high α shown by one participant at the shortest IOI (300 ms) remains a puzzle.

One might ask whether there could be a perceptual reason for the increase in α with IOI duration. Because the absolute magnitude of the perturbations increased with IOI duration in the present design, the tap-tone asynchronies generated by the perturbations also increased. Larger asynchronies may have been easier to detect and thus may have led to the larger α . However, it must be kept in mind that the PCR functions were strongly linear. If detectability of asynchronies had mattered, the slope of the PCR function should have been reduced for perturbation magnitudes near zero. Such a change in slope has never been found in numerous past studies (see Repp, 2005, for a review); on the contrary, the slope of the PCR function tends to decrease for perturbations beyond $\pm 10\%$ of the IOI duration (Repp, 2002a, 2002b). The evident independence of the PCR function from conscious perception of perturbations and asynchronies is one of the findings that led me to favor a phase-resetting explanation of phase correction in which discrete and emergent timing processes compete with each other.

As I predicted, there was little difference in the results for the two perturbation types, PS and EOS. Even if participants

had been explicitly instructed to ignore EOS perturbations, the relatively small size of the perturbations might have prevented an effect of instructions (Repp, 2002a, 2002b). Nevertheless, it is remarkable that the unnecessary PCRs to EOS perturbations increased as much with IOI duration as did the necessary PCRs to PS perturbations. A perfect PCR following a PS maximizes the probability of synchrony on the next tap, whereas a perfect PCR following an EOS results in a systematic deviation from synchrony that subsequently needs to be corrected. Evidently, participants (including myself) were unable to prevent PCRs from happening in the EOS condition, which is further proof of the automaticity of the PCR.

One question that future studies need to address is whether an increase in α up to 1 is also found when α is estimated from the time series of asynchronies according to the methods of Vorberg and Schulze (2002). Such a study would require synchronization with perfectly isochronous sequences with a similar range of IOI durations. To my knowledge, the two different ways of estimating α have never been compared directly. Moreover, a third method of estimating α is now available, which requires synchronization with adaptively timed sequences (Repp & Keller, 2008; Vorberg, 2005). Although more time-consuming, this method might be the most precise one, and replication of the present findings with this new approach would be a worthwhile project.

The evident nonlinearities in individual data also require further investigation. Intertap interval duration (which covaried with IOI duration in the present study) may not simply affect α but may also encourage strategies (e.g., mental subdivision of the beat) that in turn affect α . However, the main result here is that α can reach 1 when intervals are sufficiently long.

Finally, the present results hold only for musically trained participants, and nonmusicians remain to be tested in this paradigm. However, there is no particular reason why their behavior should be different, apart from being more variable (cf. Repp & Doggett, 2007). Arguably, synchronization and error correction skills are most relevant to music performance; this justifies the use of musically trained participants in the present study.

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