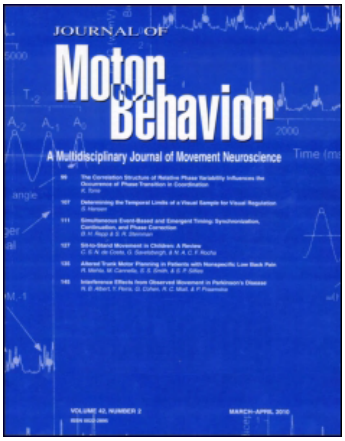

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RESEARCH ARTICLE

Tapping in Synchrony With a Perturbed Metronome: The Phase Correction Response to Small and Large Phase Shifts as a Function of Tempo

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ABSTRACT. When tapping is paced by an auditory sequence containing small phase shift (PS) perturbations, the phase correction response (PCR) of the tap following a PS increases with the baseline interonset interval (IOI), leading eventually to overcorrection (B. H. Repp, 2008). Experiment 1 shows that this holds even for fixed-size PSs that become imperceptible as the IOI increases (here, from 400 to 1200 ms). Earlier research has also shown (but only for IOI = 500 ms) that the PCR is proportionally smaller for large than for small PSs (B. H. Repp, 2002a, 2002b). Experiment 2 introduced large PSs and found smaller PCRs than in Experiment 1, at all of the same IOIs. In Experiments 3A and 3B, the author investigated whether the change in slope of the sigmoid function relating PCR and PS magnitudes occurs at a fixed absolute or relative PS magnitude across different IOIs (600, 1000, 1400 ms). The results suggest no clear answer; the exact shape of the function may depend on the range of PSs used in an experiment. Experiment 4 examined the PCR in the IOI range from 1000 to 2000 ms and found overcorrection throughout, but with the PCR increasing much more gradually than in Experiment 1. These results provide important new information about the phase correction process and pose challenges for models of sensorimotor synchronization, which presently cannot explain nonlinear PCR functions and overcorrection.

Keywords: perturbations, phase correction, sensorimotor synchronization, tapping, tempo

Phase correction is the process that keeps a discrete rhythmic movement in synchrony with an external rhythm and thus is of crucial importance in activities such as finger tapping or music performance with a metronome. It has typically been studied from an information processing perspective, which seems appropriate for discrete movements (for a review, see Repp, 2005). The corresponding process for continuous movements or internal oscillations accompanying an external rhythm, called *sensorimotor coupling* or *entrainment*, has been studied from a dynamic systems perspective (e.g., Clayton, Sager, & Will, 2005; Kelso, DelColle, & Schöner, 1990; Large & Jones, 1999). The present study is within the information processing tradition but concerns nonlinear aspects of phase correction that are not easily accommodated by present models within that tradition.

Linear models of phase correction, based on data from tapping in synchrony with a metronome, usually assume that the relevant perceptual information is provided by the asynchronies between taps and metronome sounds and that each tap corrects for a fixed proportion of the preceding asynchrony (Mates, 1994; Pressing, 1998; Vorberg & Schulze, 2002; for a general linear framework, see Jacoby & Repp, 2010). Both assumptions have already been challenged by empirical data, but model developments have not kept up with the empirical evidence. Also, some of this evidence has been limited in certain ways and therefore perhaps has not had a strong impact. The purpose of the present study, consisting of four experiments, was to replicate and extend some of these previous findings.

One kind of evidence bears on the linearity (fixed proportion) assumption. Although that assumption seems adequate for dealing with small asynchronies, such as arise when tapping in synchrony with a perfectly regular metronome, responses to timing perturbations of widely varying sizes do not seem to follow a linear function. In previous studies (Repp, 2002a, 2002b), I examined the phase correction response (PCR) as a function of perturbation magnitude (henceforth referred to as the *PCR function*). The PCR is the largely automatic compensatory shift of the tap that follows the perturbation, measured relative to when this tap would have been expected to occur in the absence of a perturbation. Two types of perturbation were used in those studies, but the one of interest here is the phase shift (PS; i.e., an unpredictable shortening or lengthening of a single interval). I found that the PCR increased linearly with PS magnitude (in accord with linear models of phase correction) when the PSs were relatively small, but increased less steeply when the PSs were large. In other words, the PCR corrected for a smaller proportion of large than of small PSs, so that the PCR function across the whole range of PS magnitudes was decidedly nonlinear (sigmoid in shape). However, this important result was obtained only at a single tempo, with a baseline metronome interonset interval (IOI) of 500 ms, and it is not known whether it generalizes to other tempi. One purpose of the present study was to fill this gap in our knowledge.

Other kinds of evidence from previous research bear on the assumption that phase correction is based on perceived asynchronies. Results challenging this assumption have been accumulating for some time (for a review, see Repp, 2005). They include findings such as the perfect linearity of the PCR function for small perturbation sizes, which together with a high detection threshold for asynchronies suggests irrelevance of at least conscious asynchrony perception to phase correction (Repp, 2000, 2001a), and the enhancement (rather than reduction or absence) of the PCR when the tap coinciding with a perturbation is omitted, so that there is no asynchrony on which the PCR could be based (Repp, 2001a).

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These findings led me to favor a model similar to one proposed by Hary and Moore (1985, 1987), according to which phase correction depends on dual time-point references—the preceding tone and the preceding tap—rather than asynchronies. In my formulation, which I refer to as the *phase resetting model*, the phase of each tap is adjusted according to the preceding tone (which involves timing a more or less constant tone-tap interval), but this phase reset is counteracted by a tendency to maintain a regular tapping rhythm. This maintenance tendency is similar to what Hary and Moore (1985, 1987) called *tap-based phase resetting*, but I conceptualized it as a kind of motor persistence or emergent timing. Although the phase resetting model is formally identical with asynchrony-based phase correction models, it differs conceptually in that it is a dual-process model with at least one time-point reference (the preceding tone). In that way, it can explain not only why perceptual thresholds for asynchronies or perturbations are irrelevant but also why immediate phase correction is typically not perfect.

The phase resetting model can also explain the more recent finding that immediate phase correction in response to perturbations actually does become perfect (on average) if the sequence tempo is made sufficiently slow (Repp, 2008). In that study, the mean PCR to small PSs (measured as the slope of the PCR function) was found to increase steadily as a function of baseline IOI and to reach 100% compensation at an IOI of about 1100 ms. Although asynchrony-based models of phase correction can accommodate this finding by simply increasing the value of the phase correction parameter (the proportionality constant) as IOI increases, such models provide no rationale for why phase correction should become more complete at slower tempi. By contrast, the phase resetting model suggests a plausible explanation: The maintenance tendency is likely to decrease as tempo decreases, due to greater discreteness of movement and greater variability of timing, and this results in loss of inertia and increased flexibility of timing. My recent results thus provide further evidence in support of the phase resetting model. However, three aspects of these data call for further investigation.

First, the increase of the PCR with IOI duration was somewhat irregular, due to large individual differences in the shape of the function. Thus, it is not entirely clear whether the function is truly linear or has some more complex shape. Second, there was a suggestion of overcorrection (i.e., the PCR exceeded the PS) at the longest IOI used (1200 ms). Indeed, if the increase of the PCR with IOI duration is linear, overcorrection must occur eventually as IOI is increased. Overcorrection is problematic for all present models of phase correction. The standard (asynchrony-based) linear model can accommodate overcorrection by setting the phase correction parameter to a value greater than 1, but it does not predict or explain overcorrection. Indeed, if the assumption is added that participants try to minimize the variance of their asynchronies (Vorberg & Schulze, 2002), overcorrection should not occur. Within the phase resetting model, overcorrection might mean that the required tone-tap interval is increasingly underestimated (and hence overproduced) once inhibition from the maintenance tendency has ceased, but it is not clear why that should occur. The existence of overcorrection at long IOIs requires further documentation. Third, the PSs in a previous study (Repp, 2008) ranged from –10 to 10% of the baseline IOI and thus increased in absolute magnitude as IOI increased. Proponents of an asynchrony-based phase correction model (if they still exist) might argue that perturbation-induced asynchronies become more detectable as their absolute magnitude increases, and that this accounts for the increase in the PCR with IOI duration. Although this argument seems implausible in view of earlier findings suggesting that conscious perception of asynchronies (or perturbations) is irrelevant to phase correction (Repp, 2000, 2001a), it still seemed prudent to address the hypothesis by using perturbations whose absolute magnitude does not change with IOI duration. These last considerations motivated Experiment 1.

EXPERIMENT 1

In Experiment 1, I aimed to replicate the finding that the PCR to small perturbations increases with IOI duration within a certain range and to determine whether that increase is linear or nonlinear. In contrast to my previous study (Repp, 2008), PSs of fixed size were used. Thus, the relative magnitude of the PSs decreased as IOI increased, which made them increasingly hard to hear and eventually entirely subliminal. Although it is well established that the conscious perception of perturbations is irrelevant to phase correction (Hary & Moore, 1987; Madison & Merker, 2004; Repp, 2000, 2001a), the prediction of an increase in the PCR while perturbations become imperceptible still seems intriguing and counterintuitive. Nevertheless, it follows from the phase resetting model, because phase resetting is assumed to occur solely with reference to the preceding shifted tone onset, not in response to a changed IOI or asynchrony. The model also predicts the increase in the PCR with IOI duration (though not overcorrection) because of the hypothesized decrease in the maintenance tendency that inhibits the PCR. On the other hand, if the PCR depended on detection of the perturbation-induced asynchronies, it should remain constant or decrease (because of increased variability of asynchronies) as IOI duration increases.

Method

Participants

The 10 participants were all musically trained. They included 8 graduate students and 1 postgraduate of the Yale School of Music (5 men, 4 women; age range = 22–26 years), who were paid for their efforts, as well as myself (age 65 years). All were regular participants in synchronization and perception experiments in my laboratory. Their primary musical instruments were piano (2), violin (3), viola, cello, oboe, and bassoon, which they had studied for 13–21 years. I am a lifelong amateur pianist with 10 years of lessons in

childhood and have much experience with simple synchronization tasks.

Materials

Tone sequences were generated online by a program written in MAX 4.0.9, running on an Intel iMac computer. The tones (piano timbre) were produced by a Roland RD-250s digital piano according to instructions from the MAX program and were presented over Sennheiser HD280 pro headphones. All tones had the same pitch (C4, 262 Hz), the same nominal duration (40 ms), and the same comfortable intensity. The baseline IOIs were 400, 600, 800, 1000, or 1200 ms. Each sequence contained 10 PSs (i.e., changes of a single IOI) whose magnitudes ranged from –25 to 25 ms in steps of 5 ms (not including zero). They occurred in random order and were separated by 5–7 unchanged IOIs, this number also being a random variable, hence the exact number of tones varied from sequence to sequence.

Procedure

Participants sat facing the computer and tapped with one hand on a Roland SPD-6 electronic percussion pad, held on the lap. They were instructed to start tapping with the third tone in each sequence and to keep tapping in synchrony with the tones until they stopped. It was pointed out that some small deviations from regularity might occur in the metronome. Each participant completed eight blocks of five randomly ordered trials each, with each trial representing a different baseline IOI duration. The session took less than 1hr.

Analysis

Asynchronies between taps and tones were calculated such that a negative asynchrony indicates that the tap preceded the tone. The PCR to each perturbation was calculated as the difference between the asynchrony of the tap following the PS and the asynchrony of the tap that nominally coincided with the PS.[1] For each IOI duration condition, the PCRs for the same PS magnitude in different trial blocks were averaged before regressing these averages onto PS magnitude (the PCR function). The slope of the PCR function (which must pass through the origin because absence of a PS implies absence of a PCR) was the measure of the mean PCR, expressing it as a proportion of PS magnitude. Because the PSs were small and fixed while the variability of taps (and hence, of PCRs) increased with IOI duration, the fits of the regression lines were not impressive, but the trends were clearly linear in all cases. Mean R^2 ranged from .85 at IOI = 400 ms to .72 at IOI = 1000 ms, increasing slightly to .76 at IOI = 1200 ms.

Results

Figure 1 shows the mean PCR (the mean slope of individual participants' PCR functions at each IOI) as a function of IOI duration. A one-way repeated measures analysis of variance (ANOVA) with Greenhouse-Geisser correction confirmed that the mean PCR increased with IOI duration, as predicted, $F(4, 36) = 8.71$, $p = .001$, and orthogonal polynomial contrasts showed that only the linear trend of that increase was significant, $F(1, 9) = 36.94$, $p < .001$. On average, phase correction was perfect at IOI = 800 ms, and at the longest IOI (1200 ms) there was significant overcorrection, $t(9) = 3.61$, $p < .01$.

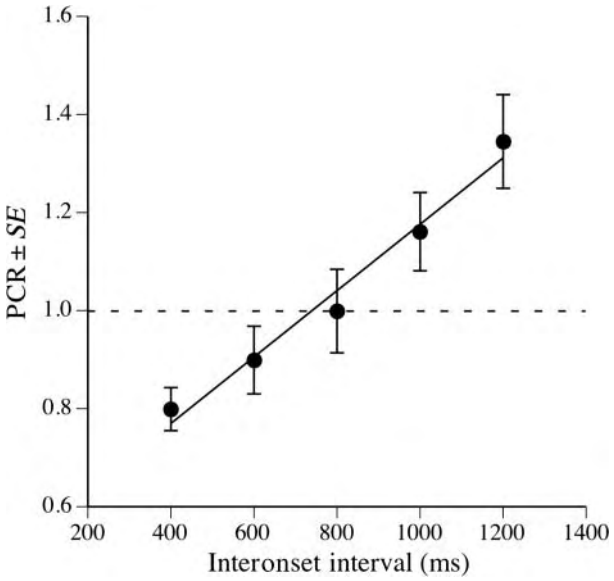

FIGURE 1. Mean phase correction response (PCR) as a function of baseline interonset interval in Experiment 1, with standard error bars and a regression line. The dotted horizontal line indicates complete phase correction (PCR = 1).

Discussion

The results of Experiment 1 replicate the increase of the PCR with IOI duration found in a previous study (Repp, 2008; Pressing, 1998). However, the increase in the PCR with IOI duration was more clearly linear than it was previously, PCRs were generally larger, and consequently there was more overcorrection at the longest IOI. The slope of the increase (0.00068) was also steeper than in the earlier study (0.00049). A mixed model ANOVA on the data for the IOI durations shared by the two experiments (only I participated in both studies) showed the difference in mean PCR to be significant, $F(1, 16) = 6.99$, $p = .018$, although the difference in slope was not reliable. The difference in mean PCR may just be a difference in participant groups, however, and not due to the use of fixed-size perturbations.[2]

As expected on the basis of the phase resetting model, the decreasing perceptual salience of the perturbations as IOI increased did not prevent an increase in the PCR. The 50% detection threshold for changes in a single IOI is typically around 6% (Friberg & Sundberg, 1995), but tends to be lower (4–5%) for musicians (Repp, 2001a, 2010). The present PSs

ranged from less than 7% of the shortest IOI (400 ms) to less than 2% of the longest IOI (1200 ms) and thus were largely or entirely subliminal at the slower tempi. Nevertheless, they elicited healthy PCRs, which seems surprising from the perspective of an asynchrony-based model of phase correction but not from that of the phase resetting model, according to which the tap following a shifted tone is shifted along with the tone, due to a planned constant response delay (tone-tap interval). However, the finding of overcorrection at long IOIs is problematic for both models, as noted previously.

Overcorrection has previously been observed after a tempo change in a sequence (Jacoby & Repp, 2010; Michon, 1967; Repp, 2001b; Repp & Keller, 2004). In that case, overcorrection is easily attributed to the engagement of a second error correction process, *period correction*, which comes into play when an expected tempo change is detected, and whose effects are assumed to be additive with those of phase correction (Repp & Keller, 2004). However, it is difficult to appeal to period correction in the present context not only because there were no expected tempo changes, but also because the PSs were subliminal. In tapping with a seemingly isochronous sequence, period correction is assumed to be dormant.

Another context in which overcorrection has been found is during synchronization with an "adaptively timed" sequence, which is controlled by a computer with phase correction capability (Repp & Keller, 2008). If the computer's phase correction parameter is sufficiently large, its combination with human phase correction results in overcorrection because the human parameter apparently stays constant. This is reflected in a negative lag-1 autocorrelation of asynchronies, which reflects the rapid oscillations introduced by correction of initial overcorrection. However, this result was obtained in a somewhat unusual paradigm. The present experiment provides the clearest demonstration so far that overcorrection can occur in response to simple phase perturbations, and it is presently not clear how extant models should be amended to predict or even merely accommodate such overcorrection at slow tempi. Perhaps a nonlinear dynamic approach is required to explain this phenomenon, or period correction is somehow engaged by phase shifts (i.e., local tempo changes) at slow tempi, even when they are not consciously detected. For further evidence of overcorrection at long IOIs, see Experiment 4.

EXPERIMENT 2

In previous studies (Repp, 2002a, 2002b), I found that the PCR is relatively smaller for large than for small phase perturbations, regardless of presentation mode (blocked or randomly intermixed). However, this result was obtained at a single tempo (IOI = 500 ms), and the purpose of Experiment 2 was to investigate whether it holds across a range of tempi. The range of IOIs was the same as in Experiment 1, and the PSs were large and increased proportionally with IOI duration. A comparison of results for small and large PSs across the two experiments seemed legitimate in view of the previous finding that the blocked and randomized presentation of perturbation sizes give similar results. I also found previously that participants reacted in different ways to positive PSs (delays) of half a cycle, sometimes inserting an extra tap (Repp, 2002b), and it was of interest whether that strategy would be observed again at different tempi.

Method

Participants

The participants were the same as in Experiment 1.

Materials

Tone sequences were constructed in the same way as in Experiment 1; only the perturbations were larger and proportional to IOI duration. They ranged from –50 to 50% of the IOI in steps of 10% (not including zero).

Procedure

Participants again completed eight blocks of five trials each in a session lasting less than an hour. They were informed that there would be large deviations from regularity in the metronome and that they should try to get back into synchrony after each perturbation as quickly as possible.

Analysis

Several unexpected but interesting anomalies in responses to large PSs required some modifications in data analysis.[3] Therefore, these responses are discussed here, rather than in the Results section.

In previous investigations of the PCR to large phase perturbations, I either reported no anomalies (Repp, 2002a; Experiment 6) or found that participants frequently inserted an extra tap following the largest positive PS (50%; Repp, 2002b; Condition 1). The extra tap occurred approximately at the time at which a tap would have occurred in the absence of a perturbation; this is illustrated schematically in Figure 2B, with Figure 2A showing the normal response (i.e., the one that maintains a 1:1 relation between tones and taps). Such extra taps were rare in the present experiment (a total of 29 instances) and derived mainly from a single participant. They occurred more often at long (1000–1200 ms) than at short IOIs (22 vs. 7 instances), and more often for 50% than for 40% PSs (19 vs. 9 instances, with a single occurrence after a 20% PS). These extra taps were simply ignored in computing the PCR.

A much more common occurrence (407 instances total) was the omission of taps following large negative PSs, a strategy that had not been observed in previous studies. Such omissions were shown quite consistently by 6 of the 10 participants. The omitted tap was either the one nominally coinciding with but actually lagging behind the advanced tone (referred to as the first tap; 323 instances), or the following (second) tap (i.e., the one that would have exhibited the

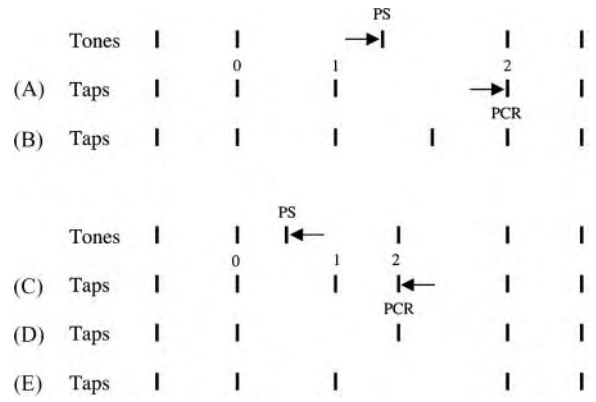

FIGURE 2. Schematic illustration of different phase correction response (PCR) strategies with large phase shifts (PSs). (**A**) Positive PS, normal PCR. (**B**) Positive PS with extra tap. (**C**) Negative PS, normal PCR. (**D**) Negative PS with first tap (1) omitted. (**E**) Negative PS with second tap (2) omitted. Tap 0 provided the reference asynchrony for PCR calculation. In this idealized figure, PSs are ± 50%, PCRs are perfect, and small asynchronies are not shown.

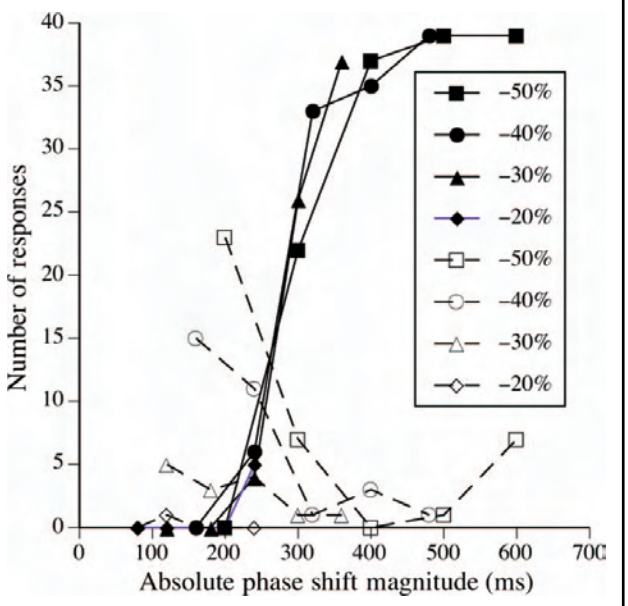

FIGURE 3. Numbers of skipped first taps (filled symbols) and skipped second taps (open symbols) following a negative phase shift (PS) in Experiment 2, shown as a function of absolute PS magnitude for each of four levels of relative PS magnitude.

PCR; 84 instances), as illustrated in Figures 2D and 2E, respectively (Figure 2C shows the normal response). These tap omissions followed an interesting pattern that is depicted in Figure 3. There the numbers of first- and second-tap omissions are plotted as a function of absolute PS magnitude, with the connected data points representing equal relative PS magnitudes (% of IOI duration) across different baseline IOI durations. It is evident that first-tap omissions (filled symbols) occurred predominantly with PSs of –300 ms or more and did not depend on relative PS magnitude. By contrast, second-tap omissions (open symbols) occurred mainly with PSs of less than –300 ms and did appear to depend on relative PS magnitude, being more common with larger relative PSs (i.e., at shorter baseline IOI durations). These responses were too scarce and idiosyncratic for tests of statistical reliability.

Moreover, in those cases where the first tap was not omitted following a large negative PS (Figure 2C), which applied to 4 participants in particular, there was evidence of incipient phase correction in that tap. See Experiment 3B for a more detailed analysis of that phenomenon. This had the consequence of reducing the PCR of the second tap, if it was calculated as the difference between the second- and first-tap asynchronies, as in Experiment 1. When the first tap was omitted, of course, the PCR could not be calculated in this way at all. Therefore, regardless of whether the first tap was omitted, and for positive PSs as well, the PCR in Experiment 2 was calculated as the difference between the asynchrony of the second tap and the asynchrony of the tap preceding the PS (labeled tap 0 in Figure 2), plus the PS magnitude.[4] In cases in which the second tap was omitted, the PCR could not be calculated (taking the asynchrony of the following tap, which showed virtually perfect phase correction, as the basis of calculation would have overestimated the immediate PCR). This resulted in some missing data points for those participants who omitted the second tap consistently.

The PCRs thus obtained were analyzed as in Experiment 1 by averaging them across trials, plotting the averages as a function of PS magnitude, and deriving the slope of the regression line (the PCR function) as the measure of the mean PCR. Because random variability relative to the PS and PCR sizes was much smaller than in Experiment 1, linear regression fits were generally better, with mean R^2 values increasing from .83 to .98 as IOI increased. In addition, separate regression lines were fit to the PCRs for negative and positive PSs, for two reasons: First, to document that negative PSs were more difficult to adjust to than positive PSs. Apart from the tap omissions already mentioned, which caused some missing data points, there were sometimes nonlinear trends in individual data for negative PSs (a flattening of slopes toward long IOI values). Mean R^2 values ranged from .62 to .91 for negative PSs, but from .77 to .99 for positive PSs, which generally showed very linear PCR functions. Second, the mean intercepts of these separate regression lines were of interest: If small PSs elicit larger PCRs than large PSs, then the regression lines for large PSs should not pass through the origin. Rather, the regression line for negative PSs should have a negative intercept, whereas the regression line for positive PSs should have a positive intercept. Finding such a difference in intercepts (in addition to finding a difference in slopes between Experiments 1 and 2) would confirm that the complete PCR function is nonlinear. This nonlinearity is

ignored when a single regression line is fitted to PCRs for large negative and positive PSs.

Results

The mean PCRs are shown in Figure 4A as a function of IOI duration. As expected, the mean PCR for negative and positive PSs combined increased with IOI duration, $F(4, 36) = 33.77$, $p < .001$. The linear, $F(1, 9) = 91.11$, $p < .001$, and quadratic trends, $F(1, 9) = 7.00$, $p = .027$, were significant, because the increase was largest initially, at the shorter IOIs. Also, as predicted, the PCRs were significantly smaller than those in Experiment 1, $F(1, 9) = 18.24$, $p = .002$.[5]

The PCR function for positive PSs was similar to that for all PSs combined, although it showed only a linear trend and large individual differences at the shortest IOI. However, the mean PCRs for negative PSs were clearly smaller and seemed not to increase with IOI duration beyond 600 ms. A two-way repeated measures ANOVA revealed significant main effects of PS direction, $F(1, 9) = 17.69$, $p = .002$, and IOI duration, $F(4, 36) = 7.55$, $p = .005$, though the interaction fell short of significance, $F(4, 36) = 2.67$, $p = .081$, due to large variability.

Figure 4B shows the mean intercepts of the PCR functions for positive and negative PSs, respectively. As predicted, the intercepts for positive PSs were positive, whereas those for negative PSs were negative. Negative intercepts decreased further as IOI duration increased, but this was not shown by all participants, as can be seen in the large standard errors. An ANOVA revealed significant main effect of PS direction, $F(1, 9) = 37.82$, $p < .001$, and IOI duration, $F(4, 36) = 6.06$, $p = .003$, whereas the interaction fell short of significance, $F(4, 36) = 2.76$, $p = .077$.

Discussion

The findings of Experiment 2, in conjunction with those of Experiment 1, confirm and extend to a wide range of tempi the previous single-tempo finding that PCRs to large PSs are proportionally smaller than PCRs to small PSs (Repp, 2002a, 2002b). One simple interpretation of this difference is that it is easier to make a small change in the timing of a planned movement than it is to make a large change. However, this is probably not the whole story. Whereas the PCR to small PSs increased linearly with IOI duration and showed increasing overcorrection at IOIs longer than 800 ms (Figure 1), the PCR to large PSs increased nonlinearly with IOI duration and seemed to reach an asymptote around 1 (Figure 4). Although this asymptote needs to be confirmed by investigating even slower tempi, there is no evidence here that overcorrection occurs in response to large perturbations. It is likely that large timing adjustments are under cognitive control, and this may prevent overcorrection (rather than period correction being engaged and augmenting the PCR). Overcorrection in response to small perturbations happens without participants' awareness and seems to be the consequence of an autonomous dynamic process.

The mean PCR (regression slope) for small perturbations within a certain range (±R) can be estimated from the mean slopes (S) and intercepts (I) of the PCR functions for large negative (n) and positive (p) perturbations (Figure 4) as $[(I_p + S_p \times R) - (I_n - S_n \times R)]/(2 \times R)$. If R is assumed to be 10% of the IOI, the resulting small-perturbation PCR estimates for the five IOI durations are 0.99, 0.96, 1.10, 1.11, and 1.17. These values are not only larger than those for large

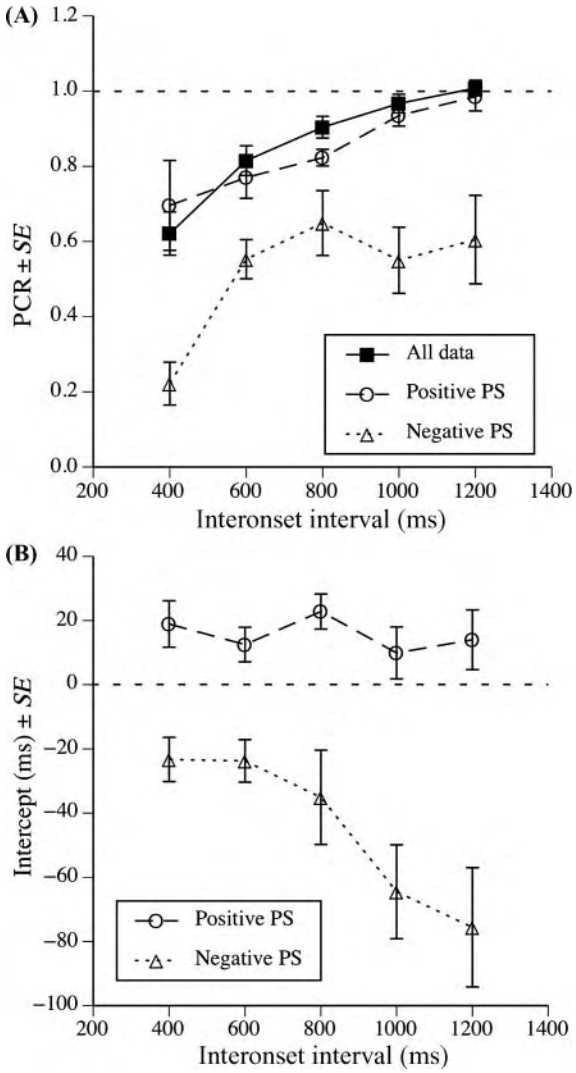

FIGURE 4. (**A**) Mean phase correction response (PCR; mean slope of the regression of PCR on phase shift [PS] magnitude) as a function of baseline interonset interval for all PSs and for positive and negative PSs separately in Experiment 2, with standard error bars. The dotted horizontal line indicates perfect phase correction (PCR = 1). (**B**) Mean intercepts of the PCR–PS regression line for positive and negative PSs separately, with standard error bars. The horizontal line indicates zero.

perturbations, but they also show an increase with IOI duration as well as overcorrection at the longer IOIs. However, the function is considerably flatter than the one obtained in Experiment 1 (Figure 1). If instead the range of small perturbations is assumed to be fixed and independent of IOI, then setting R to 75 ms (a value consistent with the data of Repp [2002a, 2002b] for IOI = 500 ms) results in slope estimates that are quite close to those observed in Experiment 1, namely 0.74, 0.90, 1.12, 1.24, and 1.39. Although this exercise must be regarded with caution in view of the large variability of the slopes and intercepts for large negative PSs, it suggests that the inflection point of the nonlinear (sigmoid) function relating the mean PCR to PS magnitude is independent of IOI duration. If so, it may correspond to a transition from automatic to consciously controlled phase correction based on detection of a change in asynchrony, although it is not immediately clear why the detection threshold for changes in asynchrony should be independent of IOI duration, considering that the variability of asynchronies increases steadily with IOI duration. Consciously controlled phase correction is tantamount to period correction, which in some recent studies has indeed been assumed to depend on perception of asynchronies (Repp & Keller, 2008; Schulze, Cordes, & Vorberg, 2005; see also Jacoby & Repp, 2010).

The tap omissions observed in response to large negative PSs are informative about the temporal constraints under which phase correction operates. Tap omission was by no means necessary; some participants hardly ever omitted a tap. However, those participants who did omit taps—presumably to prevent a large asynchrony from occurring—did so only under certain conditions. In particular, the tap that nominally coincided with a large negative PS (but in fact lagged behind the shifted tone) was omitted only when the PS was larger than 200–250 ms, regardless of tapping rate. This is consistent with studies in the literature that indicate that 200 ms or more is required to inhibit a prepared motor response (e.g., Verbruggen, Logan, Liefooghe, & Vandierendonck, 2008). If the coincident tap was not omitted, it often showed an early PCR if the PS was sufficiently large (in ms), and the following tap (the one to show the PCR proper) was sometimes omitted, but only if the PS was less than 300 ms and at least 30% of the IOI. This evidently reflected a difficulty of advancing a tap so that it followed soon upon the preceding tap. For example, a perfect PCR to a 50% PS at IOI = 400 ms required the next tap to be advanced by 200 ms, which left little time for its movement planning and execution. Therefore, the tap was either advanced insufficiently or omitted. By contrast, delaying a tap at this tempo did not cause any problems. Clearly, it was more difficult to advance than to delay taps in response to large perturbations. This difference was already evident in Repp (2002a, 2002b), but it is more striking here.

EXPERIMENT 3

The slope estimation exercise just described raised the interesting question of whether the change in slope of the function relating the PCR to PS magnitude—the change that marks the boundary between small and large PSs—occurs at a fixed absolute PS magnitude that is independent of tempo (e.g., 75 ms) or at a magnitude that is a fixed proportion of the baseline IOI (e.g., 15%), or perhaps at some point between these two extremes. Addressing this question properly requires including small and large PSs in the same experiment as well as varying tempo. This was the purpose of Experiment 3.

Experiment 3 had two parts, A and B. In Experiment 3A, PS magnitude was varied within the same range of absolute magnitudes at each tempo. Thus, if the change in slope occurred at fixed absolute (negative and positive) values of PS, then the PCR functions for different IOIs should have sigmoid shapes with similar inflection points, differing only in slope. The inflection points could differ for negative and positive PSs, but both should remain constant across IOIs. However, if the point of slope change depended on tempo, it should occur at larger PS magnitudes when the tempo is slower and might in fact not be observable within the chosen range of PSs at the slowest tempo. In Experiment 3B, the PSs were varied within a fixed range of percentages of the baseline IOI duration. If the point of slope change occurred at a fixed percentage of the IOI, then the three PCR functions should have similar inflection points when PCR and PS are expressed as percentages of IOI. If the change of slope occurred at a fixed absolute PS value, it should occur sooner (i.e., at a smaller percentage of IOI) at a slow tempo than at a fast tempo.

Method

Participants

The 10 participants were similar in age and musical training to the participants in Experiments 1 and 2. In fact, 3 (a violinist, a violist, and the author) were the same as previously, and another (a pianist) had been a regular participant in synchronization experiments 1 year before the present study. The other 6 were newly recruited from the Yale School of Music and included a composer–pianist, violist, flutist, trombonist, guitarist, and harpist.

Materials

Tone sequences were constructed in the same way as in Experiments 1 and 2. Three baseline IOIs were used: 600, 1000, and 1400 ms. In Experiment 3A, PSs ranged from –150 to 150 ms in steps of 15 ms, not including zero. In Experiment 3B, they ranged from –30 to 30% of the baseline IOI in steps of 3%, not including zero. Each trial contained 20 PSs, one of each magnitude, randomly ordered and separated by 3–5 unchanged IOIs. The separation was smaller than in previous experiments, to reduce the length of trials.

Procedure

Participants completed nine blocks of three trials each in each of two 1-hr sessions, which were 2–3 weeks apart. They were informed that there would be deviations from regularity in the metronome and were told to adjust quickly so as to maintain synchrony. In Experiment 3B, they were also asked not to insert or skip taps.

Analysis

PCRs were calculated in two ways: with reference to the preceding tap (the one nominally coinciding with the PS), as in Experiment 1, and with reference to the tap preceding the PS, as in Experiment 2.[6] This was done to confirm the equivalence of the two methods when PSs are small, and to assess early PCRs of the tap nominally coinciding with (but actually following) large negative PSs. Such early PCRs should show up as a difference between the PCRs calculated according to the two methods. The main data represent PCRs calculated according to the second method.

Results

Experiment 3A

Figure 5A shows the mean PCRs as a function of PS magnitude (in ms). As predicted, the PCR functions had sigmoid shapes that were fit well by cubic functions, as shown. The slope of the function was steeper at the slower tempi; this represents the predicted increase in phase correction efficiency. The deviations of the functions from the identity line (the positive diagonal, where PCR = PS) are shown in Figure 5B. Here it can be seen more clearly that the PCR overcorrected for both negative and positive PSs at the slower tempi (i.e., the data points are below zero and above zero, respectively), whereas at the fast tempo it did not fully correct for negative PSs and barely overcorrected for positive PSs. The question of main interest was whether the deviations from linearity occurred at the same absolute PS magnitude at each tempo. This is not so easy to judge by eye alone.

The data were first subjected to a two-way repeated measures ANOVA with IOI and PS (21 levels because the origin was added to the data) as variables. Apart from the obviously significant main effect of PS, there was a significant IOI × PS interaction, $F(40, 320) = 12.47$, $p < .001$, because the difference among IOI conditions increased with PS magnitude, due to the different slopes of the functions. The main effect of IOI, which would reflect different negative–positive asymmetries of the functions, did not reach significance, $F(2, 16) = 3.05$, $p = .081$.

The main effect of PS was then decomposed into single degree of freedom polynomial contrasts. The linear contrast was naturally highly significant, but in addition the quadratic, $F(1, 8) = 17.86$, $p = .003$, and cubic, $F(1, 8) = 18.76$, $p = .003$, contrasts were significant. The (positive) quadratic contrast reflects an asymmetry between the PCRs to negative and positive PSs, with the former being smaller than the latter, whereas the (negative) cubic contrast reflects the sigmoid shape of the functions. Separate one-way ANOVAs (with PS as the variable) on the PCRs at each tempo confirmed that all three PCR functions deviated significantly from linearity. Whereas the quadratic contrast (indicating asymmetry) was significant only for IOI = 600 ms, $F(1, 8) = 50.55$, $p < .001$, the cubic contrast was significant at all three tempi: IOI = 600 ms, $F(1, 8) = 11.81$, $p = .009$; IOI = 1000 ms, $F(1, 8) = 8.22$, $p = .021$; and IOI = 1400 ms, $F(1, 8) = 5.52$, $p = .047$.

To assess the effect of IOI on the shape of the functions, one-way ANOVAs (with IOI as the variable) were conducted on the linear, quadratic, and cubic coefficients of the cubic

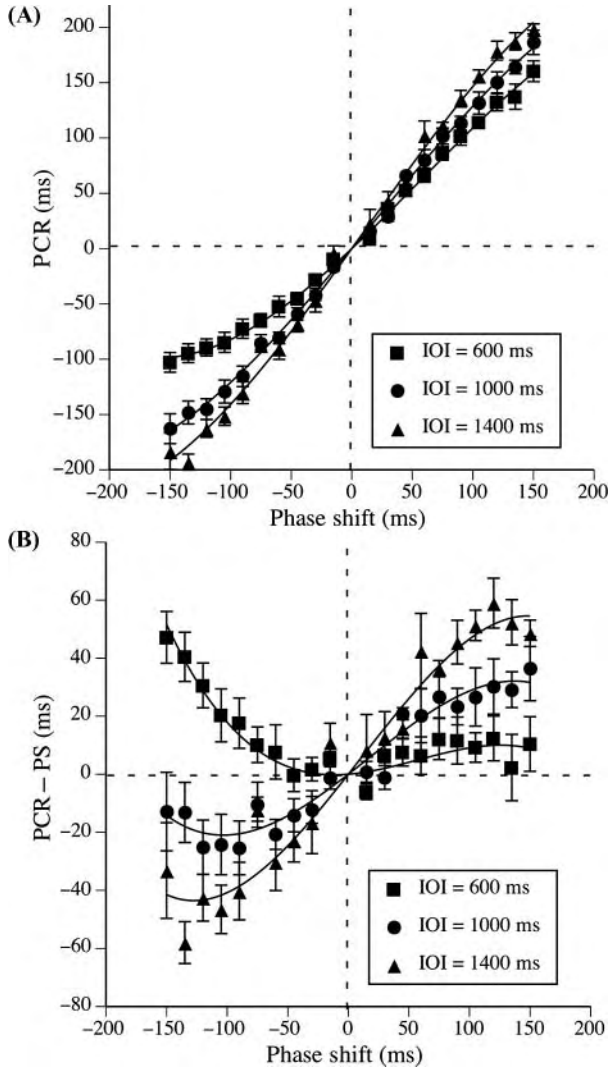

FIGURE 5. (**A**) Mean phase correction response (PCR) as a function of phase shift (PS) magnitude at three interonset interval (IOI) durations in Experiment 3A. (**B**) The same data plotted as deviations from the identity line (PCR = PS). All data have been fit with cubic functions. Error bars are standard errors.

functions fit to individual participants' PCR data.[7] IOI had significant effects on the linear, $F(2, 18) = 23.00$, $p < .001$, and quadratic, $F(2, 18) = 4.24$, $p = .037$, coefficients, but not on the cubic, $F(2, 18) = 0.08$, $p = .843$. The first effect reflects the increase in slope with IOI duration. The mean linear coefficients at the three tempi were 1.03, 1.33, and 1.53, respectively, indicating increasing overcorrection, especially of the smaller PSs. The second effect reflects a reduction in the asymmetry between PCRs to negative and positive PSs as IOI increased. The nonsignificance of the third effect indicates that the sigmoid functions were similar in shape, with similar inflection points. This result is consistent with the hypothesis that the change in slope occurs at a certain absolute PS magnitude, such as ±75 ms.

To test more specifically the hypothesis that the PCR functions are linear for PSs in the range of ±75 ms, the preceding analyses were repeated with the data restricted to this range (PS then had 11 levels). In the overall ANOVA, the cubic contrast was no longer significant, $F(1, 8) = 1.34$, $p = .28$, though the quadratic contrast still was, $F(1, 8) = 11.27$, $p = .01$. One-way ANOVAs on the data for each IOI duration revealed no significant cubic contrasts, only significant quadratic contrasts (asymmetries) at IOI = 1000 ms, $F(1, 8) = 5.54$, $p = .046$, and at IOI = 1400 ms, $F(1, 8) = 6.09$, $p = .039$. Thus, the results are compatible with the hypothesis of linearity between ±75 ms, at least with linearity for negative and positive PSs considered separately. It is clear from inspection of Figure 5B that linearity did not extend much beyond ±75 ms.

Finally, the PCR estimates obtained with the two methods of calculation were compared to determine whether there was any evidence for early phase correction on the tap nominally coinciding with (but really following) negative PSs. A three-way repeated measures ANOVA (with the variables of method, PS, and IOI) was conducted on the data obtained with the two methods for PSs of –105 to –150 ms. No effect involving method was even close to significance, which indicates that no early phase correction occurred, and that the two methods yielded nearly identical PCR estimates.

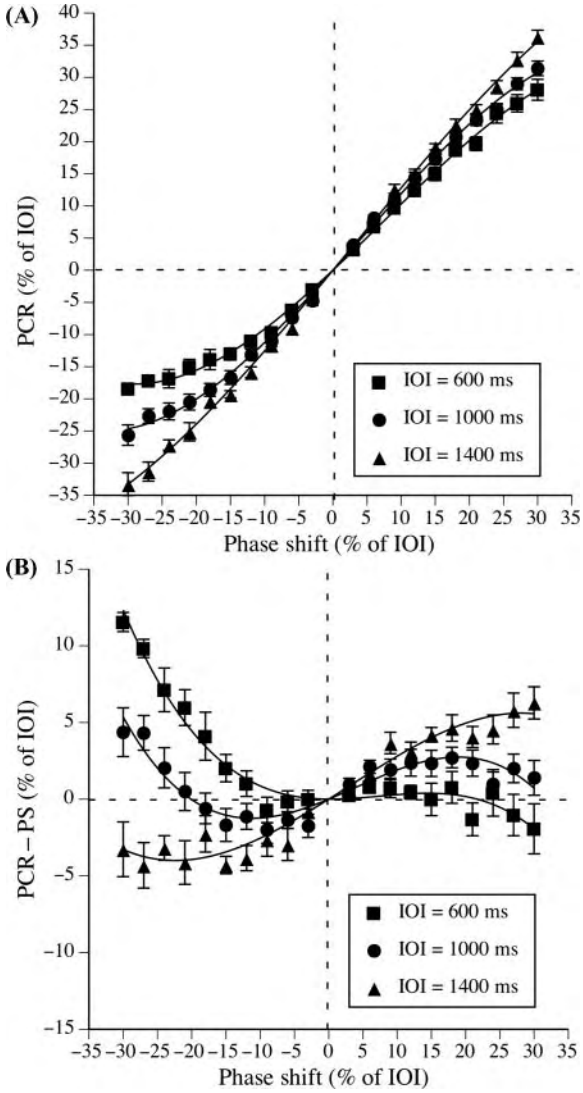

FIGURE 6. (**A**) Mean phase correction response (PCR) as a function of phase shift (PS) magnitude at three interonset interval (IOI) durations in Experiment 3B. (**B**) The same data plotted as deviations from the identity line (PCR = PS). All data have been fit with cubic functions. Error bars are standard errors.

Experiment 3B

The results of this experiment are shown in Figure 6A in which the mean PCRs and PS magnitudes are expressed as percentages of IOI. Again, the data were fit well by cubic functions. The slope of the functions increased with IOI duration, as before. The deviations of the functions from the identity line are shown in Figure 6B. Again, overcorrection occurred for negative and positive PSs at IOI = 1400 ms, whereas at IOI = 600 ms incomplete correction occurred for negative PSs. At IOI = 1000 ms, the pattern was mixed. Most surprisingly and contrary to both hypotheses, the deviations from linearity seemed to occur progressively later as IOI duration increased.

The overall ANOVA yielded, besides the obviously significant main effect of PS, a significant main effect of IOI, $F(2, 16) = 6.76$, $p = .017$, and an IOI × PS interaction, $F(40, 320) = 19.67$, $p < .001$. The main effect of IOI reflects the decrease in asymmetry of the PCR functions as IOI increased, and the interaction reflects the increasing divergence of the functions as PS magnitude increased, due to the different slopes of the functions. Decomposition of the PS main effect into polynomial contrasts showed not only the linear contrast but also the quadratic, $F(1, 8) = 34.76$, $p < .001$, and cubic, $F(1, 8) = 32.73$, $p < .001$, contrasts to be significant. Again, the (positive) quadratic contrast reflects asymmetry around zero, whereas the (negative) cubic contrast reflects sigmoid shape.[8] One-way ANOVAs on the individual PCR functions confirmed that all three deviated

significantly from linearity. In particular, the cubic contrasts were significant at IOI = 600 ms, $F(1, 8) = 11.81$, $p = .009$, at IOI = 1000 ms, $F(1, 8) = 8.22$, $p = .021$, and at IOI = 1400 ms, $F(1, 8) = 5.52$, $p = .047$, whereas the quadratic contrast was significant only at IOI = 600 ms, $F(1, 8) = 50.55$, $p < .001$.

To assess the IOI × PS interaction in more detail, an ANOVA was again conducted on the coefficients of the cubic functions fit to the individual PCR data. IOI had significant effects on all three types of coefficient: linear, $F(2, 18) = 24.99$, $p < .001$; quadratic, $F(2, 18) = 8.90$, $p = .004$; and cubic, $F(2, 18) = 5.82$, $p = .019$. The first effect reflects the increase in slope with IOI duration. The mean slopes at the three tempi were 1.00, 1.19, and 1.28, respectively. The second effect reflects a decrease in the asymmetry between PCRs to negative and positive PSs as IOI increased. The third effect, in contrast to Experiment 3A, suggests changes in the sigmoid shape of the functions with tempo. However, although the hypothesis that a change in slope occurs at a fixed absolute PS magnitude predicts increasingly negative cubic coefficients as a function of IOI, the negative coefficient was in fact smallest for IOI = 1400 ms (indicating a relatively straight function) and largest for IOI = 1000 ms.

To test whether linearity might hold within ±15% of IOI duration, an ANOVA was conducted on the data within this range. Contrary to the hypothesis, the cubic contrast was significant, $F(1, 8) = 16.67$, $p = .004$, which suggests changes in the shape of the PCR function within this range. Separate one-way ANOVAs on the data for each IOI showed the cubic contrast to be significant for IOI = 600 ms, $F(1, 8) = 10.75$, $p = .011$, not quite significant for IOI = 1000 ms, $F(1, 8) = 4.68$, $p = .062$, and not significant for IOI = 1400 ms, $F(1, 8) = 2.73$, $p = .137$. Thus, contrary to expectations but in agreement with the foregoing analysis, the PCR functions became more nearly linear as IOI duration increased, which implies that their change of slope moved to larger relative PS magnitudes.

To determine whether early PCRs occurred on the tap that nominally coincided with the PS, the PCR estimates obtained by the two methods were compared for negative PSs ranging from –9 to –30% (8 levels of PS) in a three-way ANOVA. All main effects and interactions in this analysis were highly significant, in particular the main effect of method, $F(1, 8) = 77.49$, $p < .001$, the Method × IOI interaction, $F(2, 16) = 21.79$, $p < .001$, the Method × PS interaction, $F(7, 56) = 13.64$, $p < .001$, and the triple interaction, $F(14, 112) = 5.39$, $p = .004$. Figure 7 shows the early PCRs (i.e., the difference between the estimates obtained by the two methods) as a function of PS magnitude (both expressed in milliseconds here) at the three tempi. Quadratic functions have been fit to the data. It is evident that early PCRs emerged about 150 ms after a shifted tone and increased steadily up to 420 ms, the largest PS. At that point, the early PCR amounted to 26% of the PS and an advancement of the tap by 109 ms, on average.

Comparison of Experiments 3A and 3B

The PCR functions from the two experiments, expressed as deviations from the identity line (in ms), are superimposed in Figure 8. For clarity, only the cubic functions fit to the data are shown, with data points and error bars omitted. It can be seen that the functions from Experiments 3A (solid lines) and 3B (dotted lines) do not coincide.

The differences were assessed in two-way ANOVAs (with the variables of experiment and IOI) on the coefficients of the cubic functions. The coefficient for Experiment 3B were recalculated in terms of milliseconds (rather than percentage of IOI) for this analysis. The linear coefficients increased with IOI duration, $F(2, 16) = 30.62$, $p < .001$, as observed previously, and differed between experiments, $F(1, 8) = 26.46$, $p = .001$, because the PCR functions were generally steeper in Experiment 3A than in 3B. The interaction of experiment with IOI was also significant, $F(2, 16) = 5.54$, $p = .032$, because the difference in slopes across experiments was much more pronounced at the slower tempi. Expressed differently, the slope increased more with IOI duration in Experiment 3A than in 3B (see the mean slopes mentioned earlier). Although the slope depends on the whole function and not just on the central linear segment, the slopes of these linear segments were also clearly different between experiments at the two slower tempi.

The quadratic coefficients decreased significantly as IOI duration increased, $F(2, 16) = 9.92$, $p = .002$, reflecting the previously mentioned decrease in the asymmetry of the PCR

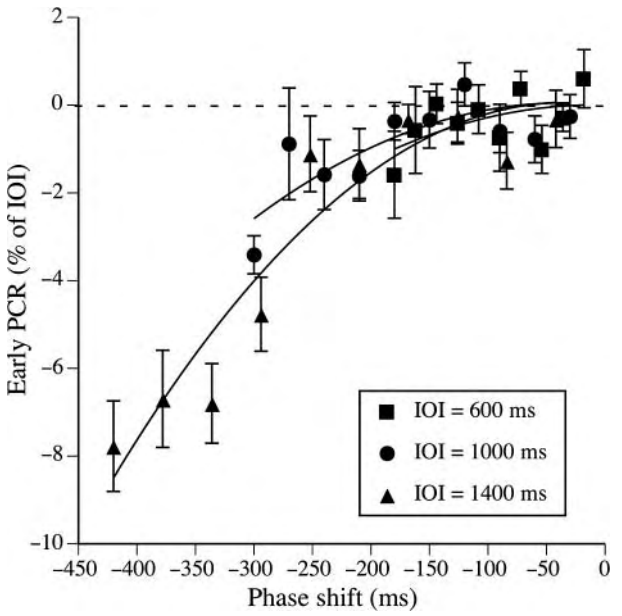

FIGURE 7. The early phase correction response (PCR) in Experiment 3B as a function of negative phase shift magnitude. The data have been fit with quadratic functions. Error bars are standard errors. IOI = interonset interval.

functions. However, they did not differ between experiments, $F(1, 8) = 1.23$, $p = .300$, and did not interact with IOI, $F(2, 16) = 0.38$, $p = .656$. Thus, both the degree of asymmetry and its decrease with tempo were similar in the two experiments. Finally, the cubic coefficients were not affected by IOI, $F(2, 16) = 0.71$, $p = .47$, which indicates similar sigmoid shapes of the PCR functions at the different tempi. Thus, when the two experiments are considered together in this way, the results are once again compatible with the hypothesis that the change in slope occurs at the same absolute PS value at each tempo (as in the analysis of Experiment 3A, but not of Experiment 3B). The cubic coefficients were smaller in Experiment 3B than in 3A, $F(1, 8) = 5.66$, $p = .045$, especially at the two slower tempi, but the interaction with IOI was not significant, $F(2, 16) = 2.12$, $p = .176$. This indicates somewhat flatter sigmoid functions with a larger medial zone of linearity in Experiment 3B than in 3A. However, the lack of an interaction is surprising for a separate one-way ANOVA on the cubic coefficients of Experiment 3B yielded a clearly significant effect of IOI, $F(2, 16) = 19.64$, $p = .001$, in agreement with the previous ANOVA on the cubic coefficients for the data expressed as percentages of IOI and with the visual impression derived from Figure 8. Therefore, it cannot really be concluded that the PCR functions of Experiments 3A and 3B had the same sigmoid shapes.

Discussion

The results of this pair of experiments add useful information to our knowledge about phase correction in sensorimotor synchronization. First, they confirm previous findings (Repp, 2002a, 2002b) that the PCR function, which relates the PCR to PS magnitude, is sigmoid in shape, with a steeper slope for small than for large perturbations. This was found to be the case at three different tempi, thus extending the earlier findings, which had been obtained at a single relatively fast tempo (IOI = 500 ms). The results also show that the steeper PCR function slope for small than for large PSs, as demonstrated in the present Experiments 1 and 2, was not simply an artifact of the range of PSs employed in these experiments. Nevertheless, this range does seem to have an effect on the slope, as slopes were shallower in Experiment 3B than in 3A, especially at the slower tempi. Thus, the PCR seems to be less vigorous when the perturbations are larger on average. This can be understood as a reduction in the strength of sensorimotor coupling when the pacing sequence is relatively more irregular in its timing.

Second, the results confirm the previously observed increase in phase correction as the tempo decreases. In both experiments, the slope of the PCR function increased with IOI duration, but it increased more steeply in Experiment 3A than in 3B, probably because the increase in average perturbation size with IOI duration in Experiment 3B, which decreased sensorimotor coupling strength, counteracted the increase in sensorimotor coupling strength as the tempo got slower.

Third, the results also demonstrate that the PCR function tends to be asymmetric, even when PS magnitude does not exceed 30% of the IOI: The PCR to negative PSs is generally smaller than the PCR to positive PSs. In other words, it is easier to delay than to advance a tap in response to a perturbation, especially when the perturbation is large or when the tempo is fast. Past experiments using only small perturbations typically have shown little asymmetry (however, for some exceptions, see Repp, 2002a). Moreover, under severe time constraints PCRs actually tend to be larger following negative PSs because the advancement of the tone leaves more time for a small PCR to be implemented (Repp, 2011).

Fourth, both experiments showed evidence of overcorrection of perturbations at the slower tempi. At IOI = 1000 ms, overcorrection was relatively small and was limited to relatively small PSs (from about –200 to 300 ms), whereas larger negative PSs were undercorrected. However, at IOI = 1400 ms, overcorrection was larger and extended well beyond ± 400 ms. Thus, although the results of Experiment 2 had suggested that overcorrection might not occur for large PSs, it seems that overcorrection of fairly large perturbations can occur at slow tempi. However, it also seems that the PCR functions tended to curve back toward zero after a point of maximal overcorrection had been reached (see Figures 5 and 6), and this may not just have been an artifact of fitting cubic functions to the data. If so, then it may still be true that very large perturbations (e.g., > 30% of the IOI) do not elicit overcorrection.

Fifth, the "early PCR" results proved informative about temporal constraints on the PCR. In Experiment 3A, where the maximum negative PS was –150 ms, there was no

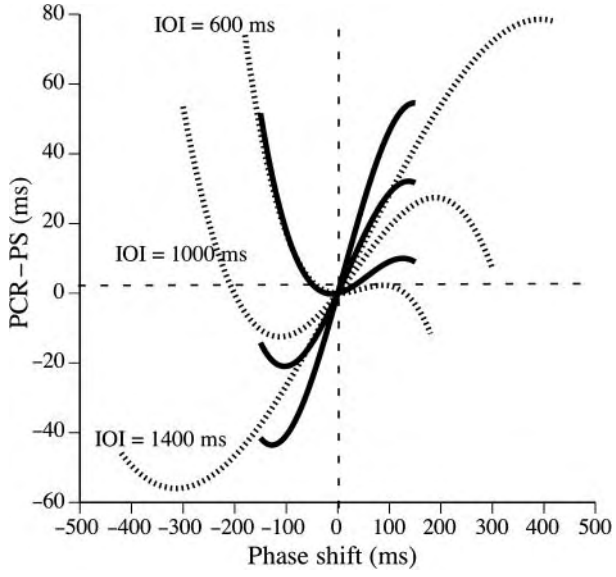

FIGURE 8. Cubic functions fit to the data of Experiments 3A (from Figure 5; solid lines) and 3B (from Figure 6; dotted lines) superimposed. IOI = interonset interval.

evidence of any early PCR on the nominally coincident tap. Experiment 3B, however, showed that an early PCR emerged just around that delay and increased steadily as the negative PS increased (up to a maximum of 420 ms in that experiment). This time course is consistent with recent findings concerning the temporal evolution of a PCR to a perturbation in synchronization with nonisochronous rhythms (Repp, 2011). The difference is that the PCR in this latter paradigm was not "early" because it occurred on the tap following a perturbation, and it reached full size within 300 ms. The present early PCR, by contrast, was much smaller and amounted to only a fraction of the full PCR. Under similar temporal constraints, it is clearly more difficult to shift a tap when its own temporal target has been shifted unexpectedly than when the temporal target of a preceding tap has been shifted.

Finally, the question of primary interest in this experiment was whether the change in slope of the sigmoid PCR functions (i.e., the boundary between small and large perturbations) would occur at a fixed PS magnitude (e.g., ±75 ms) or at a PS that is a fixed percentage of IOI duration (e.g., ±15%). The answer to this question proved to be not quite straightforward. Leaving aside the asymmetry of the PCR functions, which implies a later change in slope on the positive than on the negative side, the results of Experiment 3A were consistent with the hypothesis that the change in slope occurred at the same absolute PS size regardless of IOI duration, and that the functions were linear for PSs within ±75 ms. However, the results of Experiment 3B unexpectedly indicated that the change of slope moved to larger relative (and consequently to much larger absolute) PS values as IOI duration increased. In other words, when the range of PSs was proportional to IOI duration, the PCR function became increasingly linear as IOI duration increased. Thus, although it can be concluded that the PCR function is linear within a small absolute range of PSs (e.g., ±75 ms), the extent to which the linearity extends beyond this limited range seems to depend on the range of PSs employed.

EXPERIMENT 4

This experiment returned to a question raised by the results of Experiment 1. That experiment confirmed the presence of overcorrection at long IOIs, which had merely been suggested by previous (Repp, 2008) data. In Experiment 1, overcorrection started already at IOIs above 800 ms and was significant at 1200 ms. Given the linearity of the increase in the PCR with IOI duration, it seems likely that even greater overcorrection would occur at IOIs longer than 1200 ms. It is known that linear phase correction models become unstable if the phase correction parameter exceeds 2 (Vorberg & Schulze, 2002). Extrapolating from the present findings, assuming that the PCR continues to increase with the same slope, it can be predicted that the linear model may become unstable at IOIs around 2000 ms. It has been noted previously that IOI durations approaching 2000 ms represent the limits of perceived rhythmic coherence (Fraisse, 1982) and of relatively effortless synchronization (Mates, Radil, Müller, & Pöppel, 1994; Miyake, Onishi, & Pöppel, 2004). It would be interesting if that limit were related to instability of phase correction, which then could be assigned a causal role in synchronization difficulties. At the other end of the temporal continuum, the difficulty of synchronizing with very rapid auditory sequences (IOIs < 150 ms) has recently been linked to the time required for minimal phase correction (Repp, 2011). Accordingly, in Experiment 4 I investigated the PCR to relatively small phase shifts as a function of IOI duration in the range between 1000 and 2000 ms.

The experiment also offered another opportunity to examine the shapes of the PCR functions at slow tempi. Phase shifts varied between ±10% of the IOI and thus could be as large as ±200 ms. If the zone of linearity extends to a fixed absolute PS value such as ±75 ms, the PCR function should become increasingly nonlinear as IOI increases. However, if the linear zone extends to some fixed relative PS value or (as Experiment 3B suggested) increases with IOI duration even in relative terms, then the PCR functions at all IOI durations should be linear, for ±10% is well within the linear zone observed previously at a short IOI (Repp, 2002a, 2002b).

Method

Participants

The participants were the same as in Experiment 3.

Materials

Tone sequences were constructed in the same way as in the preceding experiments. Six baseline IOIs were used: 1000, 1200, 1400, 1600, 1800, and 2000 ms. Phase shifts ranged from –10 to 10% of the baseline IOI in steps of 2%, not including zero. Each trial contained 10 PSs, one of each magnitude, randomly ordered and separated by 3–5 unchanged IOIs.

Procedure

Participants completed five blocks of six randomly ordered trials each in one 1-hr session. They were informed that there would be deviations from regularity in the metronome and were told to try to stay in synchrony at all times.

Analysis

PCRs were calculated as in Experiment 1. As the largest possible negative PS was –200 ms, early phase correction was expected to be negligible.

Results

Figure 9 shows the mean PCR (slope of the PCR function) as a function of IOI duration. It is evident that overcorrection occurred at all tempi and increased with IOI duration. A one-way repeated measures ANOVA with Greenhouse-Geisser correction showed the increase to be significant,

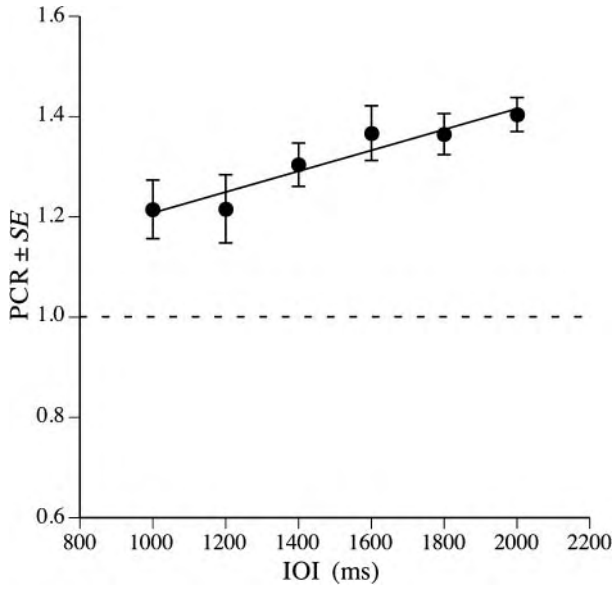

FIGURE 9. Mean phase correction response (PCR) as a function of phase shift magnitude at six interonset interval (IOI) durations in Experiment 4. Error bars are standard errors.

$F(5, 45) = 6.75$, $p = .001$, and although it seemed a bit irregular, only its linear trend was significant, $F(1, 9) = 21.22$, $p = .001$, which justifies the linear regression line shown in the figure. The slope of that line is 0.00021, which is less than one third of the slope found in Experiment 1 between IOIs of 400 and 1200 ms (Figure 1).

At each tempo, the PCR function was strongly linear, with mean R^2 values ranging from .95 to .97. A 6 × 11 repeated-measures ANOVA on the PCRs (expressed in % of IOI) with the variables of IOI and PS (zeros were added for PS = 0) yielded an obviously significant main effect of PS, no significant main effect of IOI, and an interaction that fell just short of significance after Greenhouse-Geisser correction, $F(50, 450) = 2.09$, $p = .058$, but was clearly significant ($p = .001$) if the Huynh-Feldt correction was used instead. This effect corresponds to the effect of IOI on the slope of the PCR function, reported previously. Polynomial decomposition of the main effect of PS yielded, besides the obviously significant linear trend, a marginally significant cubic trend, $F(1, 9) = 5.68$, $p = .041$, which indicates slight nonlinearity overall. Although that cubic trend did not interact significantly with the linear trend of the IOI main effect, $F(1, 9) = 5.00$, $p = .239$, it did interact with the quadratic trend of IOI, $F(1, 9) = 6.81$, $p = .028$. Consequently, the PCR functions for the six IOI durations were analyzed separately with polynomial decomposition of the PS main effect. The functions for IOIs of 1000 and 1200 ms showed a significant quadratic trend, due to slightly smaller PCRs to negative than to positive PSs. Only the function for IOI = 2000 ms showed a significant cubic trend, $F(1, 9) = 7.58$, $p = .022$.

Discussion

Taken together, the results of Experiments 1 and 4 clearly suggest a leveling off of the increase in the PCR with IOI, though not necessarily the reaching of an asymptote. Surprisingly, here there was no increase in the PCR between IOIs of 1,000 and 1,200 ms, whereas there had been a clear increase in Experiment 1 (and in Repp & Keller, 2010). This suggests that the precise shape of the function relating the mean PCR and IOI duration may to some extent depend on the range of IOIs used in an experiment.

Overcorrection was present at all IOIs between 1000 and 2000 ms, but it stayed well below the extent that would lead to instability of synchronization (i.e., a PCR of 2). Given that only the linear trend of the increase with IOI was significant, a further increase beyond an IOI of 2000 ms seems possible, although the literal pattern of the data indicates hardly any increase beyond 1600 ms. One factor that may have contributed to the slower increase in the PCR at these long IOIs is mental subdivision, which the musician participants were likely to have engaged in. It is not known at present whether mental subdivision affects the PCR, but it could well have an inhibiting effect on overcorrection, as it simulates a condition with shorter intertap intervals. Why overcorrection occurs at all is still not understood at this time.

The analysis of the shapes of individual PCR functions adds little to the results of Experiment 3. Only the function at the longest IOI showed a significant cubic nonlinearity, and that is hardly sufficient evidence for a fixed absolute limit to the linearity zone, which was hypothesized to be at a relatively small value (such as ±75 ms). The data are more consistent with the conclusion that PCR functions are generally linear for PSs within ±10% (or more) of the IOI duration. They do not replicate the result of Experiment 3B that the functions become more linear as IOI increases, but that result was obtained with shorter IOIs and a wider range of proportional PS values, so comparisons are difficult to make.

SUMMARY AND CONCLUSION

The present results fill some gaps in our knowledge concerning the parameters that affect the error correction process or entrainment that underlies sensorimotor synchronization. Experiment 1 confirmed that the PCR to small PSs in a metronome increases linearly with metronome interval duration, ultimately resulting in overcorrection, even when the perturbations are subliminal. Overcorrection presents a challenge to present models of phase correction, which can implement it as a parameter value but cannot explain why it occurs. Experiment 2 demonstrated that the phase correction response to large PSs is smaller than that to small PSs over a wide range of tempi and shows no overcorrection. Responses to large negative PSs proved revealing about

temporal limits on phase correction and movement planning. By combining small and large PSs in a single design, Experiment 3 confirmed that the PCR function is sigmoid in shape at widely different tempi, and that some overcorrection of relatively large PSs can occur. The inflection point of the sigmoid curve seemed to depend on the range of PSs. These results generalize previous findings across a wide range of tempi, which is essential for modeling the underlying processes. Finally, Experiment 4 showed that the PCR, showing overcorrection, still increases with IOI duration beyond 1000 ms but more slowly than at shorter IOIs.

The results thus document more thoroughly than previous research two kinds of nonlinearity that future improved models of sensorimotor synchronization will have to take into account: (a) the mean PCR increases linearly as a function of IOI duration up to 1000–1200 ms (with this value possibly depending on the range of IOIs used), but then increases at a much slower rate; and (b) the PCR increases linearly with PS magnitude up to some point and then increases more slowly, resulting in a sigmoid PCR function whose inflection point may depend on IOI and PS range. Furthermore, the results revealed an asymmetry between PCRs to large negative and positive PSs, with the former tending to be smaller, and they documented early PCRs following large negative PSs. The database concerning sensorimotor synchronization has been enriched, but the understanding of the effects is still very incomplete.

NOTES

1. This is equivalent to subtracting the baseline IOI from the interval between these two taps. In the absence of a PCR, the expected intertap interval would be equal to the baseline IOI.

2. This conclusion is supported by comparison with another, as yet unpublished data set (Repp & Keller, 2010) obtained from the same participants as in Experiment 1 (except for one who differed). PSs ranged from –10 to 10% of IOIs, as in Repp (2008), and IOIs ranged from 400 to 1300 ms. The mean PCR increased from 0.83 to 1.26, and the mean slope of the increase was 0.00047. These PCRs are larger than those in Repp (2008) and more similar to those in the present experiment (a statistical comparison is problematic because the IOI values do not match precisely). The slope matches that of Repp (2008), but again the statistical difference from the present, larger slope is not significant, due to large individual differences. Thus it cannot be concluded that fixed-size and proportionally increasing small PSs yield different results.

3. A total of 20 (out of 400) trials were lost to analysis due to an unpredictable program malfunction that sometimes made sequences stop after the first two tones.

4. In Experiment 1, PCR $= a_2 - a_1 = a_2 - (a_1^* - \mathrm{PS})$, where a stands for asynchrony, the index refers to tap number (as in Figure 2), and $a_1{}^*$ denotes the asynchrony that the first tap would have had with its corresponding tone in the absence of a PS. Therefore, in Experiment 2, PCR $= a_2 - (a_0 - \mathrm{PS})$, to make the PCRs comparable to those in Experiment 1. Substituting a_0 for a_1 should make no difference as long as these asynchronies have the same expected value (i.e., the mean asynchrony). See also Experiment 3.

5. They were also smaller than those in Repp and Keller (2010), which—as noted in Note 2—resembled those of Experiment 1 and stemmed from nearly the same participant group. No statistical comparison was conducted in this case because the IOIs did not match exactly.

6. Some trials were lost due to the same program malfunction as in Experiment 2, which made some trials stop unpredictably after the second tone. The ninth block was included to fill in some of the resulting gaps in the data, and some participants did additional make-up blocks. Still, 15 trials out of 216 were lost in Experiment 3A, and 13 in Experiment 3B.

7. The statistical software (SPSS) used did not show the interactions of the polynomial contrasts of PS with IOI, only their interactions with the linear and quadratic components of IOI. These were not significant for the cubic contrast.

8. The fifth-order contrast was also significant, $F(1, 8) = 20.55$, $p = .002$, but does not have any clear interpretation.

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