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Human Movement Science 21 (2002) 1–37

HUMAN MOVEMENT SCIENCE

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Phase correction in sensorimotor synchronization: Nonlinearities in voluntary and involuntary responses to perturbations

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Abstract

When finger taps are synchronized with an auditory sequence, both a global phase shift (PS) and a local event onset shift (EOS) in the sequence elicit a phase correction response (PCR) on the next tap. The PCR to an expected PS is intended and large, whereas that to an expected EOS is unintended and smaller. PCR magnitude increases linearly with perturbation magnitude up to about ±15% of the sequence period (500 milliseconds). With larger perturbations, voluntary PCRs increase more slowly whereas involuntary PCRs reach an asymptote. These results, obtained previously in a blocked design [J. Exp. Psychol. Human Percept. Perform. (in press)], were replicated in a randomized design and in two additional task contexts that varied participants' intentions while neutralizing their expectations. Neither design nor expectations seemed to play a role. However, considerable individual differences were noted. The results confirm that phase correction is partially automatic and partially subject to voluntary control, and they provide empirical estimates of error correction functions that may be useful in formal modeling of sensorimotor synchronization behavior.

PsycINFO classification: 2330
Keywords: Sensorimotor synchronization; Phase correction; Timing; Nonlinearity

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0167-9457/02/$ - see front matter
PII: S0167-9457(02)00076-3

1. Introduction

1.1. Phase correction

Successful synchronization of a repetitive motor activity, such as finger tapping, with an isochronous sequence of perceptual events requires error correction, without which synchronization errors would be cumulative (Hary & Moore, 1987b; Vorberg & Wing, 1996). The process that accomplishes this is referred to as *phase correction*. A simple linear model of phase correction accounts well for the statistical properties of the asynchronies and inter-tap intervals obtained in tapping to an isochronous sequence (Mates, 1994a,b; Pressing, 1998, 1999; Semjen, Schulze, & Vorberg, 2000; Vorberg & Schulze, in press; Vorberg & Wing, 1996). According to that model, an internal timekeeper generates intervals which are adjusted by a proportion of the most recent asynchrony. The period of the timekeeper is assumed to be unaffected by these adjustments. A second error correction process, *period correction*, is needed to adjust the timekeeper period in response to a tempo change in a sequence (Repp, 2001b) but is assumed to play no significant role in synchronization with isochronous sequences.

Complete versions of the linear phase correction model contain additional terms that represent sources of quasi-random noise as well as processing delays that are intended to account for the commonly observed anticipation tendency (negative asynchronies) in synchronization. The present study is not concerned with mathematical modeling of noisy raw data but only with a qualitative assessment of model predictions for averaged data. Therefore, it will be sufficient to consider expected values of the model variables and adjusted asynchronies, so that the noise and delay terms can be omitted:

$$E(R_{i+1}) = E(R_i) + T - \alpha[E(a_i) - E(A)], \tag{1}$$

where $E(R)$ stands for the expected time of occurrence of a tap (R = response), T is the timekeeper period, α is the phase correction parameter (generally between 0 and 1), and the final term in brackets is an expected *relative asynchrony*, obtained by subtracting the expected average asynchrony $E(A)$ (assumed to correspond to the anticipation tendency or point of subjective simultaneity for a given individual) from the expected asynchrony $E(a_i)$ at the ith position in the sequence. When the sequence is isochronous, the expected relative asynchronies beyond the first few taps are zero, so that the last term in the equation drops out and the model merely states the truism that successive taps are expected to be separated by equal intervals. These inter-tap intervals are also expected to be equal to the event inter-onset intervals (IOIs) of the sequence.

1.2. Phase shifts and event onset shifts

Relative asynchronies are expected to deviate from zero when a perturbation occurs in the timing of the event sequence. Two kinds of perturbation are of interest here: a *phase shift* (PS) (also called "pulse change" by Michon, 1967, and

Repp, 2000, 2001a) and an *event onset shift* (EOS). They are depicted schematically in Fig. 1(a) and (b), respectively. The figures illustrate positive shifts (phase delays)

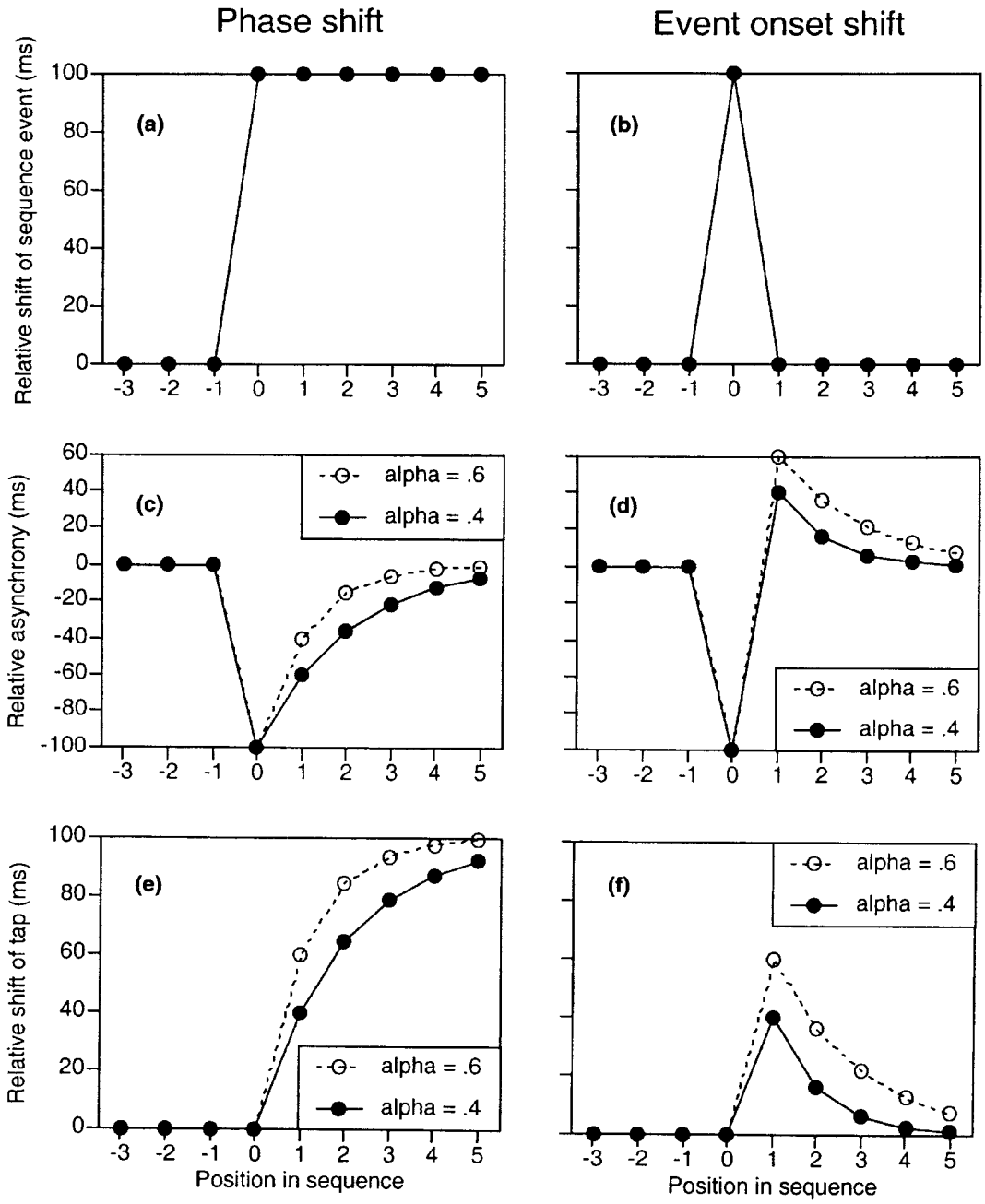

Fig. 1. Schematic illustration of two types of perturbation and expected behavioral responses predicted by the linear phase correction model, for two values of α (0.4 and 0.6): (a), (c), (e) PS; (b), (d), (f) EOS. (a), (b) Relative shifts of sequence events (by 100 milliseconds); (c), (d) relative asynchronies of taps; (e), (f) relative shifts of taps. Note that (c) = (e)–(a) and (d) = (f)–(b).

of 100 milliseconds; graphs for negative shifts (phase advances) would be mirror images of those shown. [1] In terms of event onset times, a PS consists of equal shifts (relative to the original phase) of all onsets from a certain point on, whereas an EOS consists of only a single shifted onset. In terms of IOIs (not shown directly in Fig. 1), a PS consists of a single lengthened or shortened IOI (hence the alternative name "pulse change"), whereas an EOS consists of a lengthened IOI followed by a shortened one, or the reverse. A PS thus may be regarded as a series of EOSs, whereas an EOS may be regarded as a local PS. The two perturbations are initially identical: both start with a shifted event onset or, equivalently, with a lengthened or shortened IOI. This is the perturbation point (position 0 in Fig. 1).

Let us call the perturbation magnitude Δ (delta). Then the expected relative asynchrony at the perturbation point is $-\Delta$, since an asynchrony is conventionally defined as the time of occurrence of a tap minus the time of occurrence of the closest sequence event (see Fig. 1(c) and (d)). According to Eq. (1), the tap in position 1 is now expected to be made $T + \alpha\Delta$ milliseconds later, with $\alpha\Delta$ being the phase correction. If the perturbation is a PS, the sequence event in position 1 is again shifted by Δ relative to the original phase of the sequence (Fig. 1(a)), so that the expected relative asynchrony in position 1 is $\alpha\Delta - \Delta = -(1 - \alpha)\Delta$ (Fig. 1(c)). This leads to a further phase correction of $\alpha(1 - \alpha)\Delta$, which then results in an expected relative asynchrony of $-(1 - \alpha)^2\Delta$, and so on. Thus, the relative asynchronies decrease toward zero according to an exponential function. This is also the case if the perturbation is an EOS, but here the sequence event in position 1 is not shifted relative to the original phase (Fig. 1(b)), so that the expected relative asynchrony in position 1 is $\alpha\Delta$ (Fig. 1(d)). This leads to a phase correction of $-\alpha^2\Delta$, so that the next expected relative asynchrony is $\alpha\Delta - \alpha^2\Delta = \alpha(1 - \alpha)\Delta$; the following phase correction is $-\alpha^2(1 - \alpha)\Delta$, resulting in an expected relative asynchrony of $\alpha(1 - \alpha)^2\Delta$, and so on.

As can be seen, the relative asynchronies following a PS have the opposite sign of those following an EOS. This difference conceals the fact that a PS and an EOS are initially identical (position 0) and therefore are expected to elicit the same immediate behavioral response (position 1). To compare behavioral data for PS and EOS perturbations, it is therefore preferable to replace relative asynchronies with measures of the *relative shift* of taps, which are calculated relative to the times at which the taps would have been expected to occur if there had been no perturbation (i.e., relative to the extrapolated original phase). The expected relative shift at the perturbation point is zero (assuming that the perturbation could not be predicted), and the expected relative shift of the tap in position 1 is $\alpha\Delta$ for both types of perturbation (Fig. 1(e) and (f)). Subsequently, the phase correction functions diverge: for PS perturbations (Fig. 1(e)), the relative shifts are expected to approach Δ according to the function $[1 - (1 - \alpha)^n]\Delta$, as can easily be demonstrated. For EOS perturbations (Fig. 1(f)), relative shifts are equal to relative asynchronies (except at the perturbation point), and

[1] Because the sequence IOI was not varied in this study, PSs of sequence events and taps are shown in milliseconds rather than in radians or proportions of the IOI. The term "phase shift" (PS) will be used to refer to the type of perturbation shown in Fig. 1(a), whereas the plain term "shift" will be used to denote phase shifts of taps.

thus they are expected to approach zero according to the function $\alpha(1-\alpha)^n\Delta$, as described above. The relative asynchronies (Fig. 1(c) and (d)) are the difference between the relative shifts of the taps (Fig. 1(e) and (f)) and the relative shifts of the sequence events (Fig. 1(a) and (b)).

The relative shift of the tap immediately following a perturbation (position 1 in Fig. 1(e) and (f)) will be called the *phase correction response* (PCR) (Repp, 2002a). Since the PCR is expected to be equal to Δ for both types of perturbation, the phase correction parameter α can be estimated directly from the average PCR, within confidence limits that depend on the variability of the data. Moreover, by varying Δ within an experiment, the average PCRs for the different Δ values can be examined as a function of Δ. If the function is linear, the slope of the regression line provides a good estimate of α (Repp, 2001a, 2002a). Whether this *PCR function* is in fact linear is the main topic of the present study.

1.3. The form of the PCR function

The linear phase correction model, both in the simplified form stated here (Eq. (1)) and in the more elaborate versions considered in the literature (Mates, 1994a,b; Semjen et al., 2000; Vorberg & Schulze, in press; Vorberg & Wing, 1996), assumes α to be independent of Δ. This implies that the expected PCR is a linear function of Δ with slope α. However, the model was developed to account primarily for error correction in synchronization with isochronous sequences, where there are only internal sources of timekeeper and motor variability (Wing & Kristofferson, 1973) that keep the relative asynchronies within bounds. For moderately skilled participants, the standard deviation of asynchronies is typically between 3% and 6% of the sequence IOI duration. The relative asynchronies thus vary within a range of less than $\pm 12\%$ (± 2 standard deviations) of the IOI duration. The demonstrated success of the linear phase correction model in accounting for such data suggests that α is indeed constant within this range. One way of testing this assumption directly is to examine the relative asynchronies in a particular position as a function of the relative asynchronies in the preceding position after sorting the latter into bins according to magnitude (Pressing, 1998; Repp, 2000). Alternatively, the linearity assumption can be tested by introducing small PSs in a sequence and examining the resulting PCR function (Repp, 2000, 2002a). Both methods have strongly supported the linearity assumption. This implies that phase correction is not limited by perceptual thresholds for the detection of perturbations, asynchronies, or temporal order (Koch, 1999; Repp, 2000; Thaut, Tian, & Azimi-Sadjadi, 1998). It also implies that phase correction is symmetric around zero. Although a difference in the PCRs to positive and negative PSs has occasionally been found (Repp, 2000), such asymmetries are not the rule.

However, little is known about the PCR function for perturbations beyond a narrow range of Δ values. Clearly, there has to be a limit to the range over which the PCR function is linear. Consider the extreme case of $\Delta = \text{IOI}$, which amounts to omission of one sequence event. Rather than delaying the following tap by T milliseconds (i.e., omitting the tap in position 1), participants will probably continue

tapping regularly (at least if they know that the sequence is going to continue). It is even more obvious that a PS of $\Delta = -\text{IOI}$ will not elicit any PCR because there is no change in the timing of the sequence. More generally, a PS exceeding IOI/2 is more likely to result in an advance (negative PCR) of the tap in position 2 rather than in a large delay (positive PCR) of the tap in position 1: because the first shifted tone lags too far behind the tap that theoretically goes with it (large negative asynchrony), the PCR will be based on the smaller positive asynchrony between the subsequent tap and the shifted tone. Similarly, a PS exceeding −IOI/2 is more likely to result in a positive PCR in position 0, based on the negative asynchrony between the tap in position −1 and the first shifted tone, than in a negative PCR in position 1. More complex responses, such as changes in correction strategy after a delay, are also possible (see Semjen, Vorberg, & Schulze, 1998). However, these strategies reflect changes in the information on which phase correction is based; they do not bear directly on the linearity of the PCR function and on the constancy of the phase correction parameter α. Therefore, the question can be narrowed down to asking: is the PCR function linear for perturbations between −IOI/2 and IOI/2?

Nonlinear phase correction functions have been assumed a priori by dynamic systems approaches to rhythmic coordination, based on the theory of coupled nonlinear oscillators. For example, Large and Jones (1999) consider perceptual beat tracking as involving synchronization between an internal attentional oscillator and an external event sequence, which serves as a driving oscillator (see also Large & Kolen, 1994). The two oscillators are assumed to be coupled via a sinusoidal function of their relative phase; the amplitude of the function reflects coupling strength. This phase coupling function is approximately linear in the vicinity of zero (an attractor point) but becomes markedly nonlinear as the relative phase approaches 1/4 of the period. Beyond these points, the function decreases and reaches zero at 1/2 of the period (a repeller point). This implies a PCR function that, too, is sinusoidal in shape: the PCR should initially increase linearly with Δ, then increase more slowly as Δ approaches $\pm$IOI/4, and start to decrease beyond that point, reaching zero at $\pm$IOI/2. Although the model predicts that large phase perturbations will eventually be compensated for, the *initial* response to them (i.e., the PCR) should be small.[2] Pressing (1999), too, assumes sinusoidal error correction or control functions (which are equivalent to PCR functions) and points out their local linearity. In fact, local linearity near attractor points is a common assumption in the analysis of nonlinear dynamic systems (see, e.g., Strogatz, 1994).

A different control function has been proposed by Engbert et al. (1997) in the context of a study of bimanual coordination in polyrhythmic tapping. They assumed that error correction is linear for small deviations in relative phase but shows a "saturation effect" for larger deviations (see also Engbert, Krampe, Kurths, & Kliegl, 2002). Their proposed control function is sigmoid in shape, with the width of the linear zone being a free parameter. The sigmoid function differs from a sinusoidal func-

[2] The zone of linearity can be extended by increasing the coupling strength in a continuous-time model (Large, personal communication, June 20, 2001).

tion in that it reaches positive and negative asymptotes rather than zero crossings at ±IOI/2. Also, rather than approaching repeller points (where correction occurs slowly, if at all), the function approaches points of instability, where two alternative correction strategies may be available. This seems plausible in view of the preceding considerations.

These theoretical proposals have been tested only indirectly, by applying models containing pre-specified mathematical functions to data that were not collected specifically to reveal the form of the error correction function. By contrast, the present study took a more direct empirical approach by introducing perturbations of different magnitudes and observing the average magnitude of the PCR as a function of Δ. Such empirical estimates of the control function should be of interest to proponents of both linear (stochastic) and nonlinear (dynamic) models because they provide a test of the assumptions underlying their models.

Semjen et al. (1998), who used only a few perturbation magnitudes in a somewhat unusual paradigm (sequences started while tapping was in progress), were not specifically concerned with the form of the PCR function. However, this was the main focus of a recent experiment by Repp (2002a, Exp. 6) in which PSs ranging from −250 to +250 milliseconds were introduced in sequences having baseline IOIs of 500 milliseconds. Two different ranges of PSs were presented in different blocks of trials: in one block, Δ varied between ±10 and ±30 milliseconds in 5 milliseconds steps; in the other block, it varied between ±50 and ±250 milliseconds in 50 milliseconds steps. The average PCR function was fairly linear in both ranges, but its slope was clearly steeper within the narrow range than within the wide range. In fact, without the extreme data points (for $\Delta = \pm 250$ milliseconds), the PCR function had a sigmoid shape. However, the apparently larger α obtained for $\Delta = \pm 250$ milliseconds than for $\Delta = \pm 200$ milliseconds was puzzling. Moreover, the blocked presentation of the two ranges of Δ values could have been responsible for some or all of the observed nonlinearity. The purpose of Condition 1 of the present study was to replicate this earlier experiment using a completely randomized design.

1.4. Voluntary versus involuntary phase correction

The PCR to a PS is voluntary because participants intend (and are instructed) to restore synchrony after a phase perturbation, and the PCR is the first move in that direction. A different situation arises when an EOS occurs in a sequence. A PCR to an EOS results in an undesirable asynchrony that requires further phase correction (see Fig. 1(d)). If the PCR could be suppressed, synchrony would be achieved. Therefore, participants in this task intend (and are instructed) not to react to the perturbations. Repp (2002a, Exp. 5) investigated the shape of the PCR function for EOSs. Preceding experiments in the same study had demonstrated that EOSs in auditory sequences do elicit an involuntary PCR. The average PCR increased with EOS magnitude up to Δ values of about ±100 milliseconds (±IOI/5) but then reached an asymptote, suggesting a sigmoid control function even more strongly than the data for PSs. The PCRs to large EOSs were much smaller than the PCRs to large PSs, which

indicated that participants were able to reduce but not completely suppress their PCRs. There was also an unexpected asymmetry, especially in the PCRs to small EOSs: while the PCRs to small positive EOSs increased linearly with Δ and thus were similar to the PCRs to small positive PSs, the PCRs to negative EOSs were negligible and changed little with Δ. The asymptotic PCRs to large EOSs, too, showed a tendency to be smaller for negative than for positive EOSs. This EOS experiment used the same blocked design as the PS experiment described above. It may again be asked to what extent the specific shape of the PCR function reflected the blocked presentation of different ranges of Δ values. Therefore, Condition 2 of the present study replicated the EOS experiment, using a randomized design.

In both previous experiments, participants' intentions (whether or not to react to the perturbations) were confounded with the type of perturbation. In each case, the strategy adopted (according to the instructions received) seemed appropriate. However, the known composition of the sequences in each experiment may have had an effect beyond participants' intentions. Although PSs and EOSs are initially identical (Fig. 1), participants' expectation that a permanent PS would or would not follow a shifted event may have facilitated or inhibited their PCRs, respectively. This argument also applied to Conditions 1 and 2 of the present study. Therefore, two additional conditions were included that dissociated intentions from expectations. The two perturbation types were presented in random alternation in each condition, so that participants never knew what to expect on a given trial. In Condition 3, the instructions emphasized staying in synchrony (the "PS strategy", which is appropriate for PSs but not for EOSs), whereas in Condition 4 participants were told to tap regularly without reacting to the perturbations (the "EOS strategy", which is appropriate for EOSs but not for PSs).[3] From a dynamic perspective, these instructions can be seen as a manipulation of coupling strength.

Since participants did not know which perturbation to expect, and because a PS is initially indistinguishable from an EOS, the expected PCRs were necessarily the same for the two perturbation types within each mixed condition. A difference in PCR functions between the two conditions would reflect participants' intentions only. Any difference between the PCRs to PSs in pure (Condition 1) and mixed (Condition 3) contexts under the PS strategy would suggest that the mere presence of EOSs in the mixed context influenced voluntary phase correction. Similarly, any difference in the PCRs to EOSs in pure (Condition 2) and mixed (Condition 4) contexts under the EOS strategy would indicate an effect of the mere presence of PSs on participants' ability to inhibit their PCRs. Such context sensitivity of phase correction would be an unexpected finding.

Condition 4 included a novel situation: because participants were instructed not to react to perturbations, they were expected to be out of synchrony following a PS. Their ability to maintain a steady tapping rate in the face of various phase rela-

[3] This mixed design was preferred over one in which the instructions for PSs and EOSs were simply reversed. In that case, participants would have had to adopt each strategy in full knowledge of its inappropriateness.

tionships with the continuing auditory sequence was an issue of secondary interest in this study. It was expected that there would be a strong tendency to return to a synchronous in-phase relationship with the sequence, even though this was contrary to instructions.

2. Methods

2.1. Participants

The 10 participants included 9 paid volunteers (5 women, 4 men) and the author. All were members of a regular crew of "master tappers" who had good rhythmic skills and had participated in a number of previous experiments in the author's laboratory. Their age range was 19–27, except for the author who was 56, and musical training ranged from professional level to none at all.

2.2. Sequences

Auditory tone sequences were produced on a Roland RD-250 s digital piano via a musical instrument digital interface (MIDI) under control of a MAX patch running on a Macintosh Quadra 660AV computer.[4] The tones (sounding more like pings) were of high pitch (C8: 4168 Hz), had sharp onsets, and decayed rapidly; their nominal duration was 20 milliseconds. Each sequence contained between 13 and 17 tones with a baseline IOI of 500 milliseconds. The perturbation (a PS or EOS) occurred in the 8th, 9th, 10th, 11th, or 12th position. Sequence length varied accordingly, such that 5 tones always followed the first shifted tone. In the case of a PS, these 5 tones were shifted as well (Figs. 1(a)); in the case of an EOS, they were in the original phase of the sequence (Fig. 1(b)). The perturbation magnitudes (Δ values) were 10, 15, 20, 25, 30, 50, 100, 150, 200, and 250 milliseconds, both negative (advances) and positive (delays). Thus there were 100 sequences (5 positions $\times$ 20 Δ values) containing PSs and 100 sequences containing EOSs.

In Condition 1, the 100 PS sequences were presented twice, so that each Δ value occurred 10 times. Presentation was in 10 blocks of 20 randomly ordered sequences each, such that each Δ value occurred once in each block. Condition 2 presented the 100 EOS sequences in the same format. In Conditions 3 and 4, the EOS and PS sequences were randomly intermixed and presented only once, so that each Δ value occurred five times for each perturbation type. Presentation was in 10 blocks of 20

[4] A MAX patch is a program written in the graphical programming language MAX. Due to a peculiarity of this software, the tempo of the output was 2.4% faster than specified in the MIDI instructions. Thus the baseline IOI was actually 488 milliseconds, not 500 milliseconds. The participants' key presses were registered at a correspondingly slower rate. Throughout this paper, all millisecond values are reported as they appeared in the MAX environment. Apart from the constant scaling factor, MAX was highly accurate (within 1 millisecond) in timing the sequences and registering the key presses.

randomly ordered sequences each, such that each Δ value for each perturbation type occurred once in each pair of successive blocks.

2.3. Procedure

Participants sat in front of a computer monitor which displayed the current trial number. They listened to the sequences over Sennheiser HD540 II earphones and tapped on a Fatar Studio 37 MIDI controller (a silent three-octave piano keyboard) by depressing a white key with the index finger of the preferred hand in synchrony with the sequence tones. The MIDI controller was held on the lap, and participants were asked to keep their finger in contact with the key, which moved vertically by about 1 cm. The key had a cushioned bottom contact and did not produce any audible sound unless it was struck rather hard (as was the case with 3 participants). The electronic registration of a key depression occurred during the downward movement of the key. Participants were instructed to start tapping with the second tone in each sequence.

The four conditions were presented in fixed order (2, 1, 3, 4) on different days, typically one week apart.[5] Each session lasted about 40 minutes. In Condition 1 (PSs only), the nature of the PSs was explained with a diagram, and participants were asked to stay in close synchrony with the tones throughout. (Most of them had not encountered PSs before.) In Condition 2 (EOSs only), participants were instructed to tap in synchrony with the sequences but not to react to any shifted tones. (They were familiar with this task from previous experiments.) In Conditions 3 and 4, the presence of both types of perturbation was explained with diagrams. In Condition 3, participants were asked to stay in close synchrony with the tones "as if only PSs occurred in the sequences," even if that led to asynchronies in the case of EOSs. In Condition 4, participants were asked not to react to any perturbations and to keep tapping regularly following a perturbation "as if only EOSs occurred in the sequences," even though this would result in their taps being out of synchrony for the remainder of a sequence containing a PS. Because of the novelty and potential difficulty of this last condition, a whole block of 20 sequences was given as practice in Condition 4. In the other conditions, only a few sample sequences were presented initially.

2.4. Data analysis

The data were analyzed in terms of relative shifts rather than asynchronies (see Figs. 1(e) and (f)). As is commonly found in synchronization tasks, the average asynchronies of the taps prior to any perturbation were negative and showed large individual differences. The grand average asynchrony, calculated from the three taps preceding perturbations in all four conditions, was −54 milliseconds. Seven participants showed average asynchronies between −34 and −53 milliseconds, one (the au-

[5] Conditions 1 and 2 were renumbered for expository reasons.

thor) had a rather short average value of −16 milliseconds, and two had surprisingly long average values of −99 and −135 milliseconds, respectively. [6]

Relative shifts of the taps (in milliseconds) were calculated by first subtracting appropriate multiples of the baseline IOI duration from the times of occurrence of the taps (measured from the beginning of the sequence) and then subtracting the shift of the tap at the perturbation point from the shifts of the other taps. Thus the shift at the perturbation point was defined as the zero reference, and the average relative shifts of the immediately preceding taps were expected to be close to zero also. For each participant, the relative shifts of the taps following perturbations of the same magnitude in different trials were aligned according to the position of the perturbation and averaged. The average relative shift of the tap immediately following a perturbation was the PCR, the datum of primary interest. The relative shifts of subsequent taps reflected a gradual correction (i.e., phase correction) of the asynchrony associated with the PCR and were expected to follow roughly an exponential function (cf. Fig. 1(e) and (f)), except in Condition 4.

3. Condition 1: Phase shifts only (PS strategy)

In this condition, only PSs occurred, and participants intended to adjust quickly to these perturbations in order to maintain synchrony (the PS strategy).

3.1. Results

Fig. 2(a) shows the average PCRs as a function of the magnitude of the PS in the sequence. The error bars are double standard errors, equivalent to 95% confidence intervals. The dotted diagonal line is a regression line fitted to these data (forced through the origin); its slope (an estimate of the phase correction parameter α) is 0.46. Thus, on average, the first tap following a PS compensated for 46% of the perturbation. It seems, however, that the data are not fit very well by this linear function, even though it accounts for 97.1% of the variance. The central portion of the PCR function, for PSs ranging from −50 to +50 milliseconds, is more clearly linear. A regression line fit to this subset of the data, shown by the dashed diagonal line in Fig. 2(a), has a slope of 0.64 and accounts for 99.1% of the variance. Thus, immediate phase correction was more effective for small than for large PSs. Without the data points for the largest PSs (±250 milliseconds), the shape of the PCR function could be described as sigmoid. However, the PCRs to the largest PSs were larger than predicted by a sigmoid function (as in Repp, 2002a), so that the overall shape of the function is difficult to characterize.

There was no asymmetry in the PCRs to small negative and positive PSs, in agreement with Repp (2002a), but the PCRs to large negative PSs were relatively smaller

[6] The fact that key depressions were registered before the bottom contact occurred may have added up to −20 milliseconds to the asynchronies, depending on the key velocity.

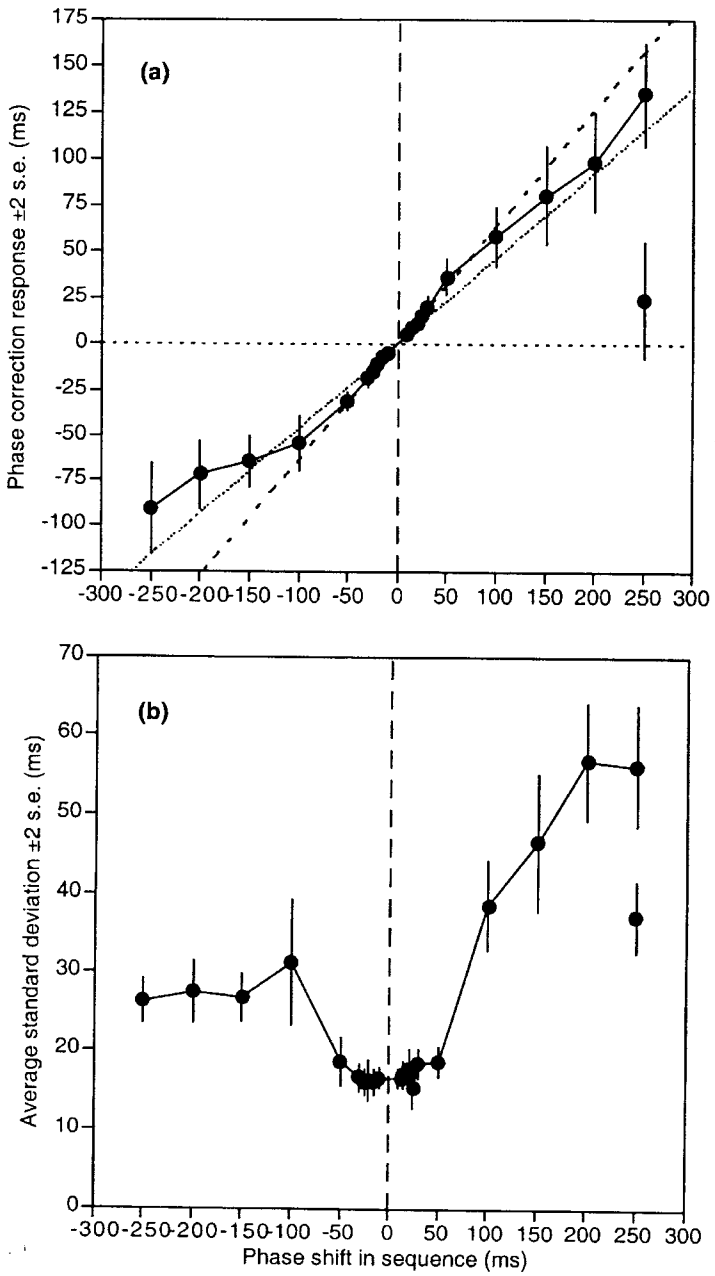

Fig. 2. (a) Average phase correction responses as a function of PS magnitude in Condition 1, with double standard error bars. The dotted regression line has been fitted to all data points, the dashed regression line only to points between −50 and +50 milliseconds on the abscissa. The isolated data point at +250 milliseconds represents the data for the accelerating strategy (see text for explanation); (b) the corresponding average standard deviations, with double standard error bars.

than those to large positive PCRs. Moreover, there was an interesting asymmetry in phase correction strategies for the largest PSs. Participants invariably responded to

large negative PSs by accelerating their taps. However, on 39% of the trials with PSs of +250 milliseconds and on 15% of the trials with PSs of +200 milliseconds, participants responded by accelerating rather than retarding their taps, in effect inserting an extra tap. (See Semjen et al., 1998, for similar observations.) Only 2 participants completely avoided this alternative strategy, though none followed it consistently. The isolated data point for PSs of +250 milliseconds in Fig. 2(a) shows the average PCR for the accelerating strategy.[7] The average PCR was still positive but much smaller than that for the retarding strategy. Thus, in most cases the first tap was not yet accelerated but was merely held back, and the acceleration happened in the course of the subsequent taps (see Fig. 4(a)). Interestingly, the average PCR was similar to that to an EOS of the same magnitude (see Fig. 5(a)), as if the acceleration strategy began with an initial non-reaction to the PS.

Between-trial standard deviations of the PCRs were calculated for each Δ value and each participant, and then were averaged across participants. Fig. 2(b) shows these average standard deviations as a function of PS magnitude, with double standard error bars. It is evident that variability was low just within the range over which the PCR function was linear (Fig. 1(a)), that is from −50 to +50 milliseconds, indicating relatively stable behavior within that region. The standard deviations, as well as individual differences in variability (error bars), increased substantially for PSs of ±100 milliseconds or more, especially on the positive side. The variability of the PCRs for the accelerating strategy at +250 milliseconds (isolated data point) was lower than that of the PCRs for the retarding strategy, which suggests that the latter was less stable at that point.

There were considerable individual differences in the shape of the PCR function, as can be seen in Fig. 3 (filled circles). However, all the participants evinced nonlinearities of the kind shown in Fig. 2(a), with a steeper and more clearly linear middle portion, and a leveling off as the PSs got large. The extent of the linear middle range varied across participants and in some cases showed asymmetries. Table 1 lists the slopes of regression lines fitted to the complete individual PCR functions and to their central portions between −50 and +50 milliseconds. For 9 of the 10 participants, the slope of the central portion was substantially steeper than the slope of the whole PCR function, $t(9) = 3.87$, $p < 0.004$.

The average relative shifts of the taps following the initial PCR approached Δ within about four taps. This is shown in Fig. 4(a) for large PSs (±50 milliseconds and beyond) and in Fig. 4(b) for small PSs (up to ±30 milliseconds). The phase correction functions in Fig. 4(a) are superimposed on a grid of functions (dotted lines) predicted by the linear phase correction model (Eq. (1)), with $\alpha = 0.46$ (the estimate derived from the complete data in Fig. 2(a)). On the negative side, the obtained functions fit the predictions reasonably well. On the positive side, phase correction was faster than predicted, suggesting a larger α, though the general shapes of the functions were as expected. Only the function representing the accelerating strategy

[7] The corresponding data point for PSs of +200 milliseconds is not shown because of the small number of trials. These trials were excluded.

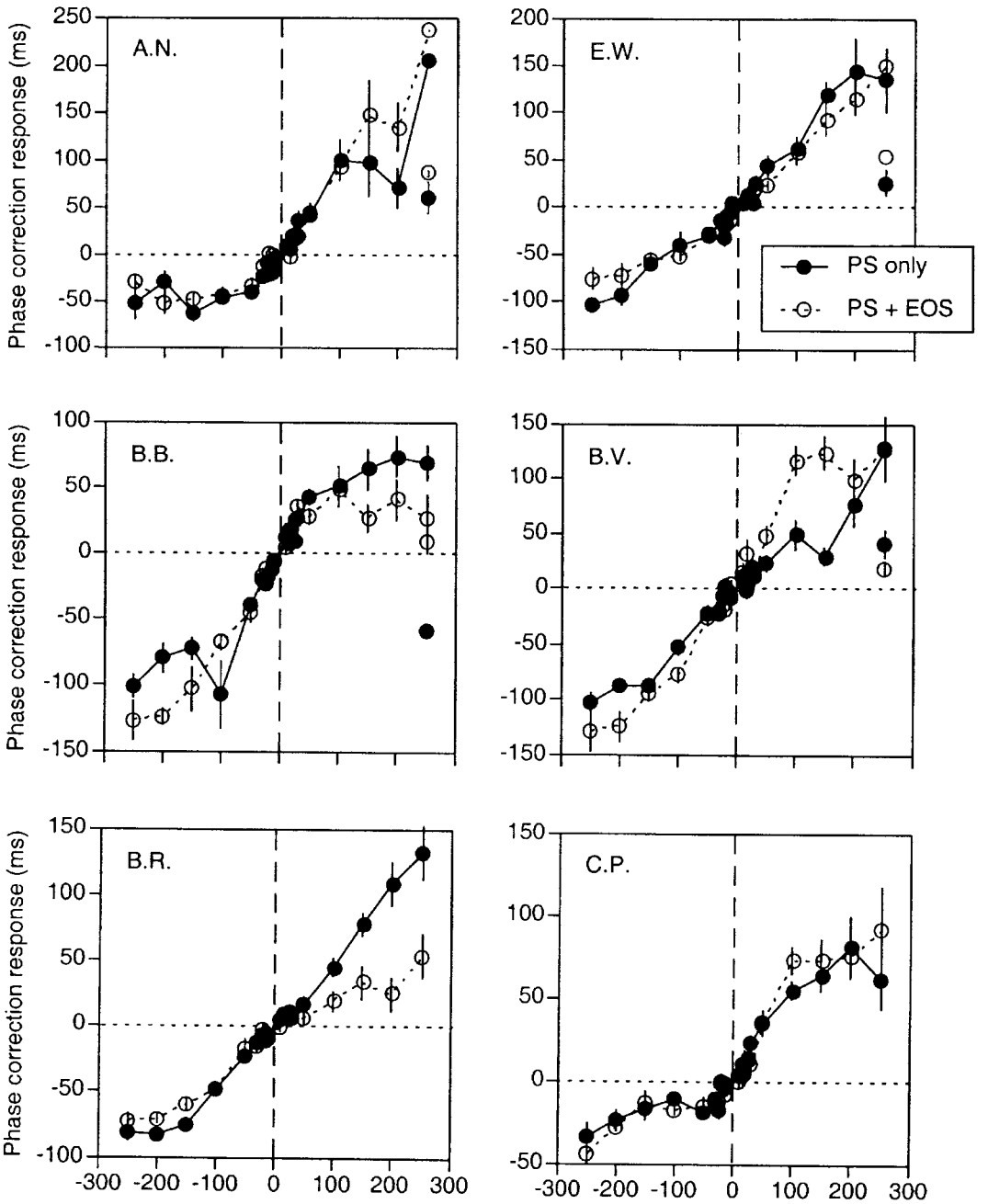

Fig. 3. Individual participant data for Conditions 1 (PS only) and 3 (PS + EOS). Average phase correction responses are shown as a function of perturbation magnitude, with single standard error bars representing trial-to-trial variability. The isolated data points represent the accelerating strategy to PSs of +250 milliseconds.

in response to PSs of +250 milliseconds (stars in Fig. 4(a)) obviously does not fit the predictions, at least in positions 1 and 2. The phase correction functions in Fig. 4(b)

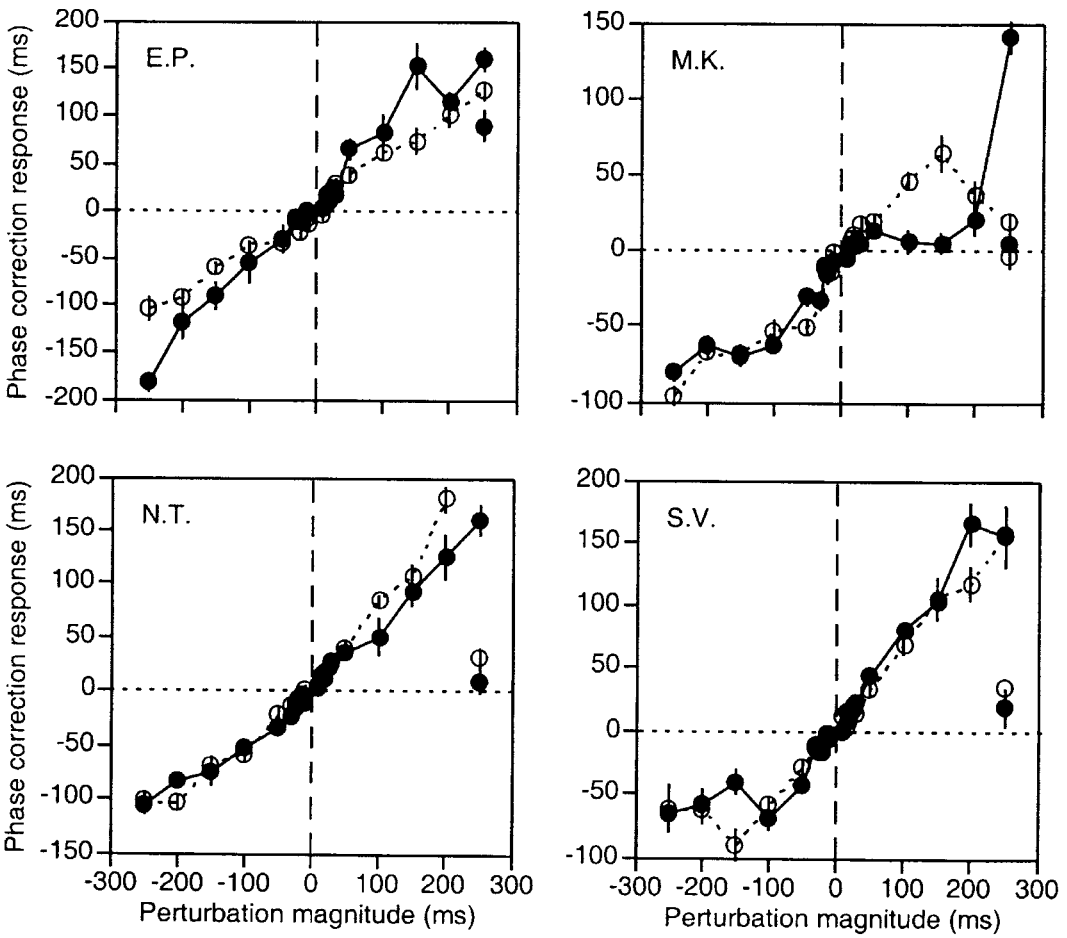

Fig. 3 (*continued*)

Table 1
Individual PCR functions in Conditions 1 and 3: Slopes of regression lines for the whole range of perturbation magnitudes ("all") and for the central range (−50 to +50 milliseconds) over which a strongly linear dependency on perturbation magnitude was observed

Participant	Condition 1		Condition 3	
	Slope (all)	Slope (central)	Slope (all)	Slope (central)
A.N.	0.470	0.839	0.551	0.659
E.W.	0.541	0.697	0.477	0.613
B.B.	0.417	0.790	0.392	0.767
B.V.	0.436	0.476	0.601	0.712
B.R.	0.456	0.397	0.266	0.301
C.P.	0.245	0.515	0.292	0.458
E.P.	0.677	0.736	0.475	0.694
M.K.	0.338	0.457	0.306	0.663
N.T.	0.539	0.715	0.609	0.616
S.V.	0.513	0.724	0.493	0.571

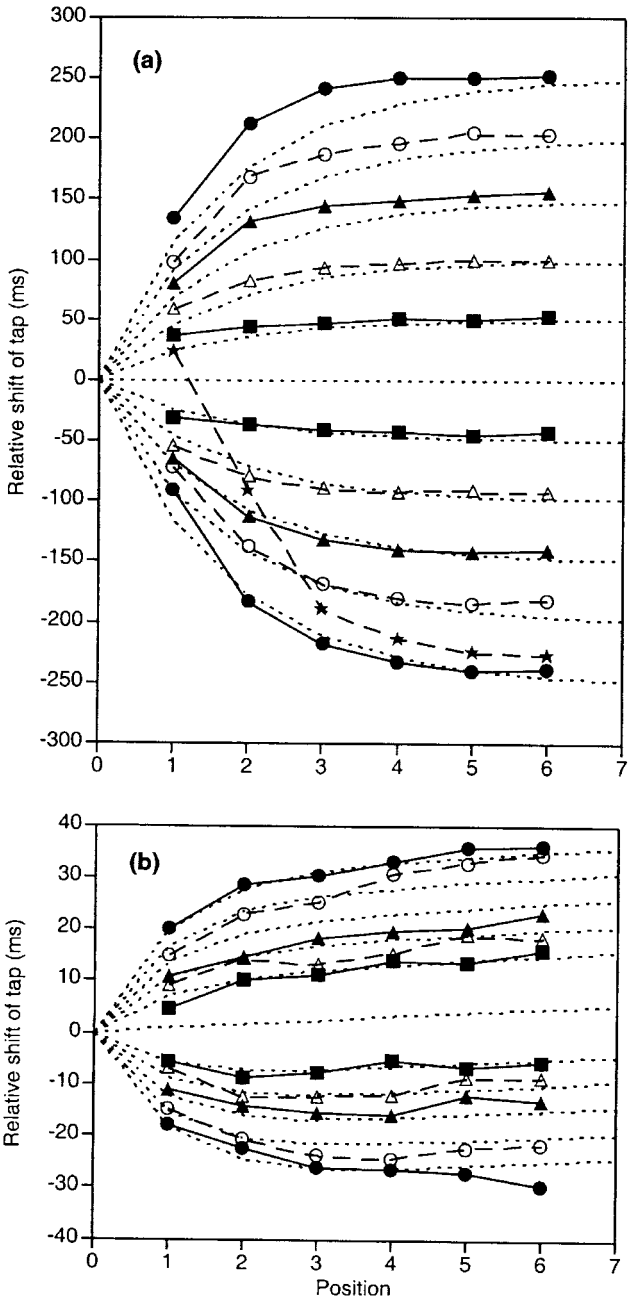

Fig. 4. Phase correction functions (average relative shift of tap as a function of position) in Condition 1, superimposed on predicted functions with $\alpha = 0.46$ (dotted lines): (a) large PSs (±50 milliseconds and beyond). The stars represent the accelerating strategy to PSs of +250 milliseconds; (b) small PSs (up to ±30 milliseconds); the predictions ($\alpha = 0.64$) here include linear drift of 0.785 milliseconds per position (see text for explanation). The Δ values can be identified from the asymptotes of the functions.

are superimposed on a grid of predicted functions with $\alpha = 0.64$ (the estimate derived from the central region of the data in Fig. 2(a)). In addition, linear drift has been

added to the predicted functions because positive drift (a slight slowing of tempo toward the end of the sequence) was evident in the data. The drift factor was estimated as the slope of a regression line fitted to the zero intercepts of regression lines fitted to the relative shifts of the taps as a function of Δ in each position. With drift taken into account, there was also a reasonable fit between predicted and obtained functions for small Δ values.

3.2. Discussion

The results of Condition 1 suggest that the linear phase correction model is valid for PSs between −50 and +50 milliseconds, and perhaps a bit beyond these values. It may not be a coincidence that these perturbations encompass the range of relative asynchronies encountered in synchronization with stationary sequences: the model was developed to account for just that situation. However, the model is insufficient to account for the PCRs to large PSs, which are proportionally smaller than those to small PSs. To account for these initial responses, a nonlinear control function must be assumed, although linearity may take over soon after the PCR because of the reduction in relative asynchrony caused by the PCR. The precise form of the control function remains somewhat unclear because of the unexpectedly large PCRs to PSs of ±250 milliseconds. Up to ±200 milliseconds, a sigmoid function is suggested, in agreement with the model of Engbert et al. (1997). In other words, the relative strength of the synchronous state as an attractor decreases somewhat as the relative asynchrony exceeds ±10% of the IOI.

The results closely replicate earlier findings obtained with small and large PSs presented in different blocks (Repp, 2002a, Exp. 6). Thus, the blocking evidently did not cause any distortion of the PCR function. The present study goes beyond the earlier experiment by providing information concerning variability, alternative strategies, individual differences, and phase correction following the PCR. The variability of the PCRs was small precisely within the range of PSs for which the linear phase correction model holds, and much larger outside that range, which indicates greater behavioral instability following large PSs. This instability was especially large after positive PSs. Large positive PSs, but not large negative PSs, called forth an alternative correction strategy in most participants. Large positive PSs differ from negative PSs in that they may be preceded by an internal reaction to the absence of an expected sequence event; this may account for the larger variability. Indeed, a large delay could have been mistaken for the end of the sequence, although participants presumably learned quickly that sequences did not end that soon. A more likely reason for the greater variability is the alternative phase correction strategy, which may have begun to have an effect before it became overt. In dynamic systems, critical fluctuations (increased variability) and critical slowing (slower relaxation or error correction) tend to occur in the vicinity of unstable states (see, e.g., Kelso, 1995). The present results suggest that the instability is greater after large phase delays than after phase advances of the same absolute magnitude.

4. Condition 2: Event onset shifts only (EOS strategy)

In this condition, only EOSs occurred, and participants intended not to react to them (the EOS strategy), in order to be in synchrony with the following tones.

4.1. Results

Fig. 5(a) shows the average PCRs as a function of EOS magnitude, with double standard error bars. It is evident that PCRs increased with EOS magnitude up to Δ values of ± 50 to ± 100 milliseconds and then reached an asymptote. Between -50 and $+50$ milliseconds, the relationship was approximately linear, though there was an asymmetry in that PCRs tended to be larger for negative than for positive EOSs (contrary to Repp, 2002a). The width of the linear zone was similar to that for PSs (Fig. 2(a)). A regression line fitted to this central range (dotted diagonal line in Fig. 5(a)) accounted for 96.3% of the variance and had a slope of 0.38, which is substantially shallower than the slope of 0.64 for the corresponding regression line for PCRs to PSs (Fig. 2(a)). Thus, the PCRs to EOSs were smaller than the PCRs to PSs even within the narrow zone of linearity. Outside that zone, the difference was huge. (Compare Figs. 5(a) and 2(a), and note the different scales on the ordinate axes.) Clearly, participants were able to control their PCRs to large EOSs, although there were large individual differences (error bars).[8]

Fig. 5(b) shows the average within-participant standard deviations of the PCRs, with double standard error bars. As with the PCRs to PSs (Fig. 2(b)), the PCRs to positive EOSs were more variable than those to negative EOSs. In contrast to the PCRs to PSs, the PCRs to large negative EOSs were no more variable than those to small EOSs. PCRs to EOSs were generally less variable than PCRs to PSs, probably because of their smaller size. (Note again the difference in ordinate scales between Figs. 2(b) and 5(b)). However, they showed larger individual differences at small Δ values (error bars). The large variability at $\Delta = +250$ milliseconds may have been due to the same instability as in the case of PSs (i.e., an alternation between – here, involuntary – reactions and successful non-reactions), but since no alternative behavioral strategy was evident in the taps following the PCR, it was not possible to distinguish two kinds of PCRs to EOSs.

As is shown in Fig. 6 (filled circles), there were considerable individual differences in the magnitude of the PCRs to large EOSs (note the different ordinate scales in different panels) and in the shape of the PCR function. All functions were clearly nonlinear, however, and all had a central zone within which the relationship to EOS magnitude was approximately linear. The slopes of regression lines fitted to the whole PCR function and to the central region (-50 to $+50$ milliseconds) are summarized in Table 2. The overall slope may be interpreted as an inverse measure of participants' success in following the "don't react" strategy. For 9 of the 10 participants,

[8] The fact that the participants all had some experience with the EOS strategy may have helped them reduce their PCRs.

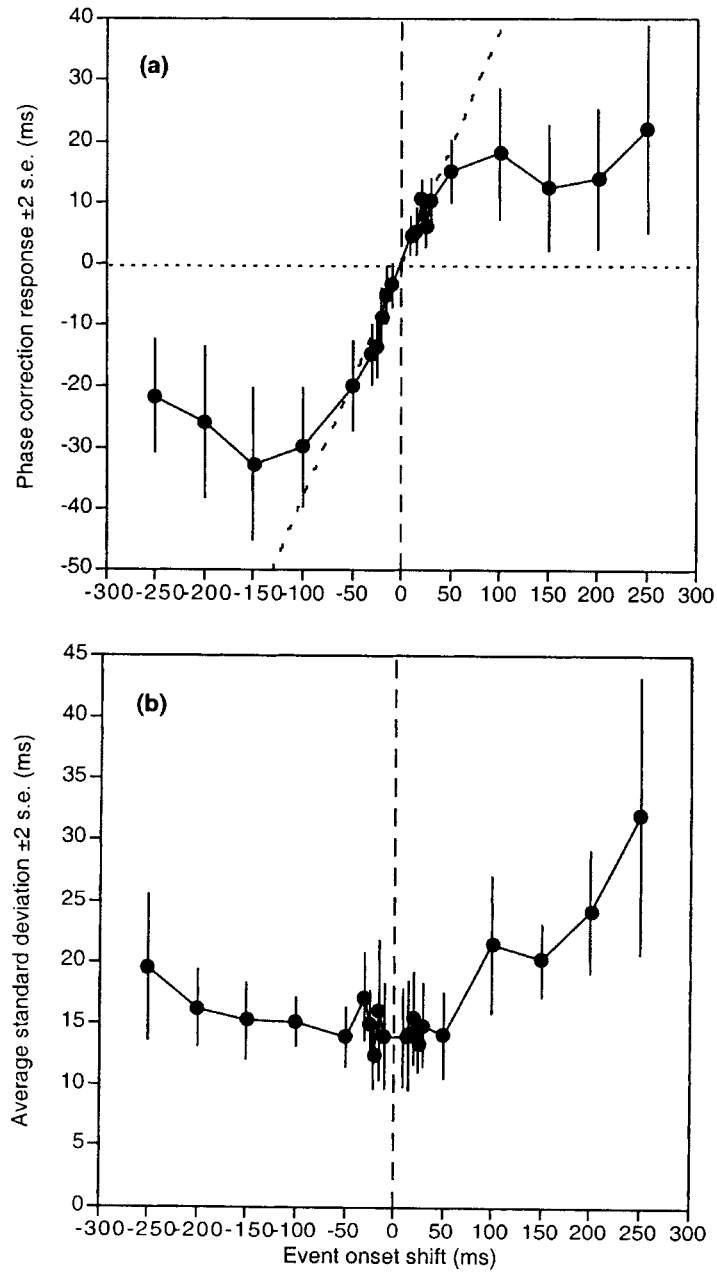

Fig. 5. (a) Average phase correction responses as a function of EOS magnitude in Condition 2, with double standard error bars. The regression line has been fitted to the data points between −50 and +50 milliseconds on the abscissa; (b) the corresponding average standard deviations, with double standard error bars.

the slope of the central portion was substantially steeper than the slope of the whole PCR function, $t(9) = 6.48$, $p < 0.001$. However, for 8 of the 10 participants, the central slope was a good deal shallower than the central slope of their PCR functions for PSs in Condition 1 (Table 1), $t(9) = 5.38$, $p < 0.001$.

The detection threshold for both EOSs and PSs, given a baseline IOI duration of 500 milliseconds, tends to be near ±20 milliseconds (Friberg & Sundberg, 1995; Repp, 2001a, 2002a). To determine whether voluntary control of PCRs occurred below the detection threshold, the PCRs to subliminal perturbation magnitudes (±10 and ±15 milliseconds) in Conditions 1 and 2 were entered into a repeated-measures ANOVA, with the variables of condition (2), absolute magnitude of Δ (2), and direction (2). The signs of the PCRs to negative perturbations were reversed to avoid trivial effects of direction. Although PCRs tended to be larger for PSs than for EOSs, the difference did not reach significance, $F(1,9) = 2.9$, $p < 0.13$. Likewise, the main effect of magnitude fell short of significance, $F(1,9) = 4.1$, $p < 0.08$. The only signif-

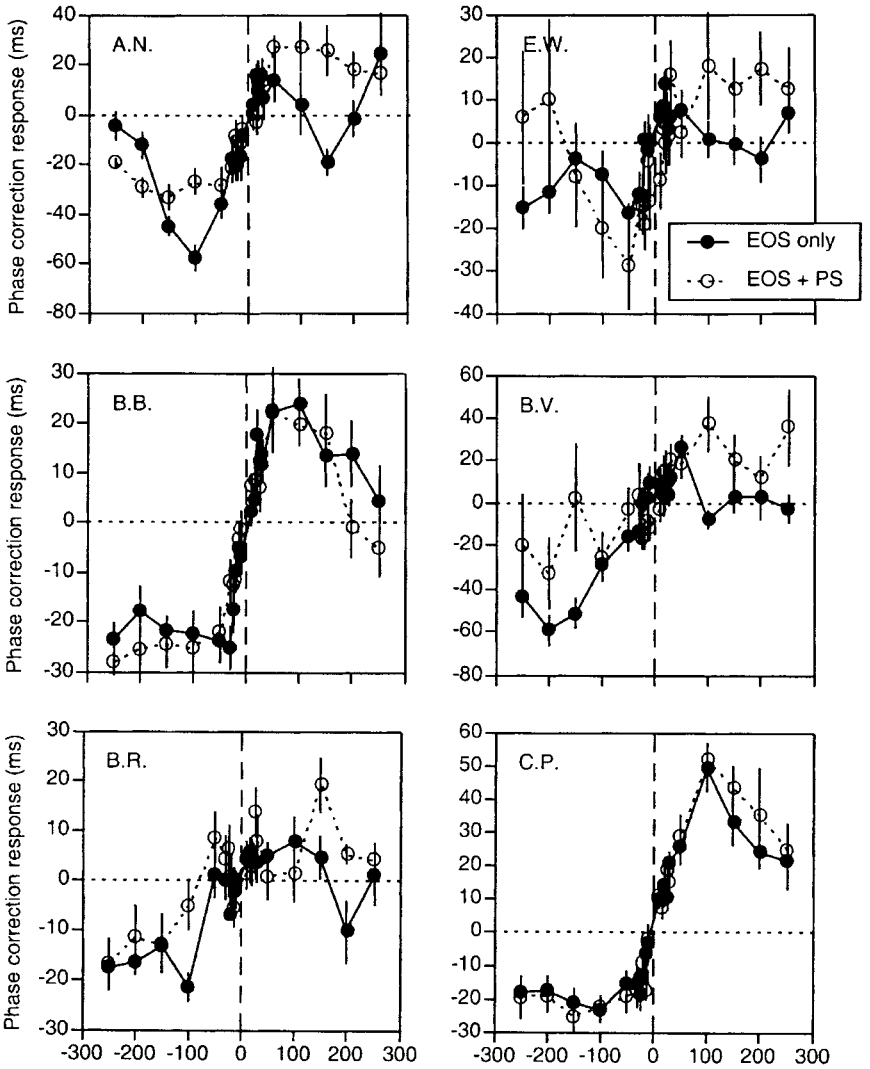

Fig. 6. Individual participant data for Conditions 2 (EOS only) and 4 (EOS + PS). Average phase correction responses are shown as a function of perturbation magnitude, with single standard error bars representing trial-to-trial variability.

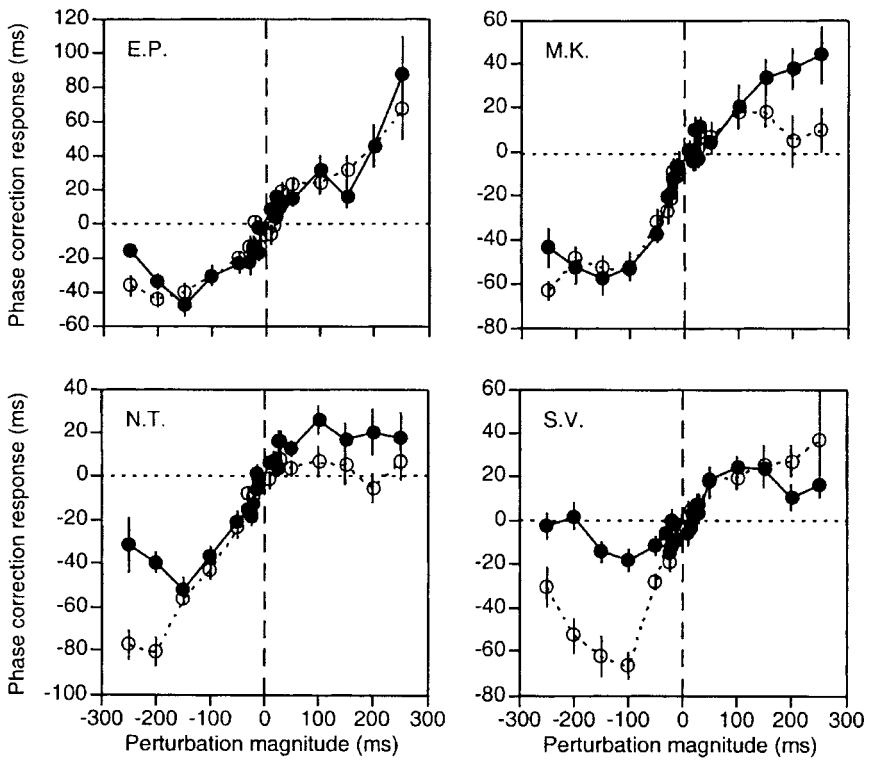

Fig. 6 (*continued*)

icant effect was the grand mean, $F(1,9) = 58.4$, $p < 0.0001$, which confirms that PCRs to subliminal perturbations occurred in both conditions (cf. Repp, 2000, 2001a). Thus, it cannot be concluded that participants exerted voluntary control over their PCR when they were unaware of an EOS.

Fig. 7 shows the average relative shifts of the taps following the PCR, which is shown in position 1. Clearly, these phase correction functions all converge upon a value near zero, although there is some scatter and positive drift, as in Condition 1 (Fig. 4). The data are superimposed on predicted functions for selected A values, with $\alpha = 0.38$ (the slope of the regression line in Fig. 5(a)) and an estimate of linear drift added. It is evident that the obtained functions, with a few exceptions, fit the predicted functions quite well from position 2 onward. However, the PCRs and the changes between positions 1 and 2 were generally larger than predicted. If this initial change were approximated by increasing α, the subsequent phase correction would seem too slow. These observations suggest a nonlinearity that extends beyond the PCR to the following tap.

4.2. Discussion

When participants try to avoid reacting to EOSs, they are rarely completely successful, even after considerable task experience. The phase correction process

Table 2
Individual PCR functions in Conditions 2 and 4: Slopes of regression lines for the whole range of perturbation magnitudes ("all") and for the central range (−50 to +50 milliseconds) over which a strongly linear dependency on perturbation magnitude was observed

Participant	Condition 2		Condition 4	
	Slope (all)	Slope (central)	Slope (all)	Slope (central)
A.N.	0.088	0.548	0.135	0.530
E.W.	0.039	0.276	0.048	0.359
B.B.	0.101	0.518	0.092	0.436
B.V.	0.129	0.323	0.126	0.345
B.R.	0.044	0.081	0.051	0.013
C.P.	0.137	0.502	0.160	0.541
E.P.	0.221	0.489	0.229	0.408
M.K.	0.232	0.418	0.181	0.416
N.T.	0.159	0.393	0.192	0.333
S.V.	0.067	0.248	0.209	0.421

definitely has an automatic component that is difficult to suppress (Repp, 2002a). The magnitude of that automatic response increases with EOS magnitude up to a point (somewhere between 10% and 20% of the IOI) and then reaches an asymptote. Thus, even though the PCR cannot be suppressed completely (except in selected conditions by some participants; see Fig. 6), its magnitude can be controlled voluntarily.

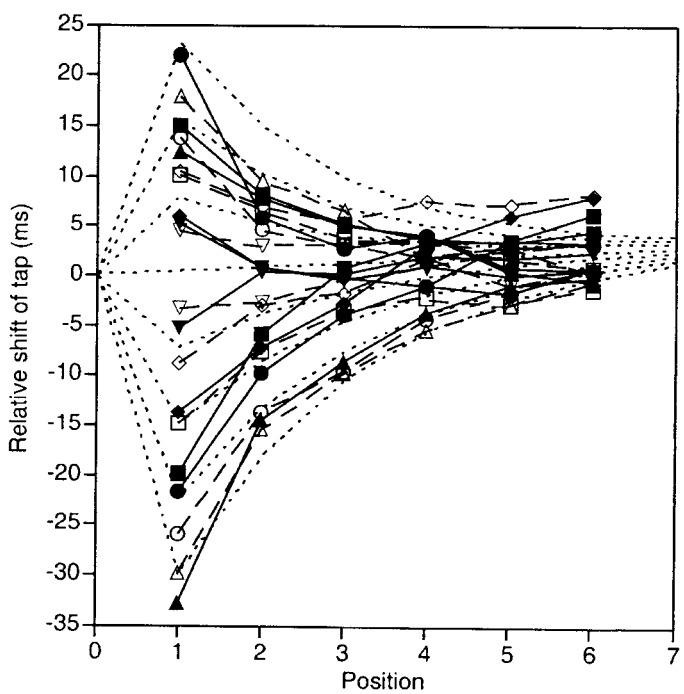

Fig. 7. Average phase correction functions (relative shift of tap as a function of position) in Condition 2, for all EOS magnitudes (not identified). The data are superimposed on predicted functions ($\alpha = 0.38$) incorporating linear drift of 0.4 milliseconds per position.

This was demonstrated previously in a similar experiment in which large and small EOSs were presented in different blocks (Repp, 2002a, Exp. 5). The blocking thus seems to have had little effect. In the earlier paper, it was proposed that the PCR asymptotes may be related to the detection threshold for timing irregularities in one's own taps. Some individuals, however, showed rather large PCRs of which they may well have been aware (see Fig. 6). The possible role of awareness of motor irregularity needs to be examined more directly in future research. The exact nature of the process that enables participants to control their PCR is not known.

PCRs to EOSs tended to be smaller than PCRs to PSs even for small perturbation magnitudes. However, there was no clear evidence of voluntary reduction of PCRs below the perceptual detection threshold for EOSs or PSs. Therefore, it is hypothesized that awareness of a perturbation is necessary for voluntary inhibition of the PCR.

Although the present results are in broad agreement with previous results (Repp, 2002a), they deviate substantially in one respect. In the previous study, PCRs to small negative EOSs were much smaller than PCRs to small positive EOSs, and there was also a tendency toward a similar asymmetry among PCRs to large EOSs. The present results show a tendency towards an asymmetry in the opposite direction. The determinants of these changing asymmetries are currently not understood. There were also considerable individual differences in that regard (see Fig. 6).

After an initial rapid decrease, correction of the asynchrony caused by the PCR to an EOS was more gradual than correction following a PCR of comparable magnitude elicited by a PS in Condition 1. This suggests that the intention not to react to an EOS also reduced the efficiency of the subsequent intended phase correction.

5. Condition 3: Phase shifts and event onset shifts mixed (PS strategy)

In this condition, sequences containing PSs and EOSs occurred in random alternation, and participants were instructed to stay in close synchrony at all times. This is the PS strategy, which is appropriate for PSs but not for EOSs. Because PSs and EOSs are initially identical (see Fig. 1(a) and (b)) and participants did not know which type of perturbation would occur in a given sequence, the respective PCRs had to be identical in this condition, within the limits of statistical variability. Therefore, PCRs were averaged across PSs and EOSs. The main question of interest was whether the resulting PCR function would be equal to that for PSs in Condition 1, or whether the occurrence of EOSs in the same condition would reduce participants' ability to respond optimally to PSs.

5.1. Results

Fig. 8 shows the results. In Fig. 8(a), the PCR function for Condition 3 (PS + EOS) is compared with that for Condition 1 (PS only). The error bars represent single standard errors here, so that the presence of significant differences between the functions can be gauged (conservatively, in view of the repeated-measures design)

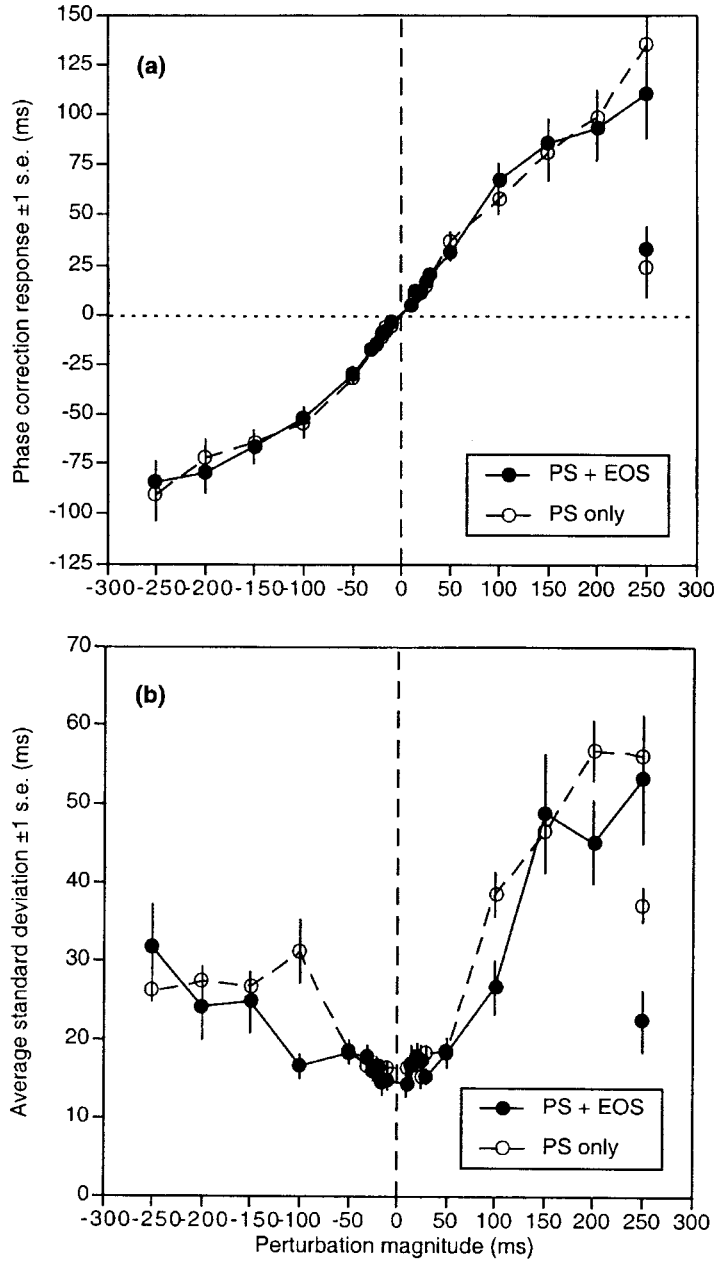

Fig. 8. (a) Average phase correction responses as a function of perturbation magnitude in Condition 3 ("PS + EOS"), with single standard error bars. The results of Condition 1 ("PS only", from Fig. 2(a)) are shown for comparison; (b) the corresponding average standard deviations, with single standard error bars.

by gaps between error bars. There are no such gaps; the two PCR functions are extremely similar.

There was again evidence of two phase correction strategies in response to large positive PSs. The accelerating strategy occurred on 20% of the trials for PSs of +200 milliseconds (these trials were excluded) and on 44% of the trials for PSs of +250 mil-

liseconds (isolated filled circle in Fig. 8(a)). By contrast, large negative PSs were always followed by accelerated tapping. In the case of large positive EOSs, there were only three trials (out of 100 for EOSs of +200 and +250 milliseconds combined) in which an acceleration strategy was observed, and a few additional ones in which the PCR was atypically small, perhaps indicating a preparation to accelerate, but was not followed by a further acceleration. (These trials were excluded as well.) Perhaps the alternative phase correction strategy for a large positive PS was triggered by an accidentally small PCR, which caused a large negative relative asynchrony; hence the much smaller incidence of such trials for EOSs, where the relative asynchrony resulting from a PCR of the same small size would be small and positive (see Figs. 1(c) and (d), for $\alpha < 0.4$).

The average standard deviations of the PCRs in Condition 3 are shown in Fig. 8(b) together with those of Condition 1. They also basically replicate the results of Condition 1, although variability of PCRs to some of the larger perturbations was clearly reduced. This could be a practice effect.

Individual differences in the PCR functions can be seen in Fig. 3 (open circles). Some participants showed significant differences between their PCRs in Conditions 1 and 3, especially on the positive side. However, the nature and direction of these differences was idiosyncratic. Table 1 lists the slopes of regression lines fitted to the individual complete PCR functions and to their central portion between −50 and +50 milliseconds. For most participants, the central portion was substantially steeper than the whole function, $t(9) = 4.04$, $p < 0.003$, as in Condition 1. The correlation between the slopes obtained in Conditions 1 and 3 was 0.55 ($d.f. = 8$, $p < 0.05$) for both overall and central slopes, which indicates only moderate reliability of individual differences in PCRs.

The post-PCR phase correction functions for PSs were very similar to those for the PSs in Condition 1 (Fig. 4) and therefore are not shown in a separate figure. Fig. 9 shows the phase correction functions for EOSs, without a grid of predicted functions in this case. The obtained functions differ from those in Condition 2 (Fig. 7) in that the initial PCRs were much larger because they were intended. The functions converge upon values slightly above zero, again due to positive drift across sequence positions. The functions for the larger PCRs show rapid correction immediately following the PCR, which is suggestive of a large α, even though the PCR was less than 50% of the EOS. This is problematic for the linear error correction model, which tries to account for the whole function with a single value of α. As in Condition 2, there seems to be a nonlinearity extending beyond the initial PCR, even in this case when the PCR was intended.

5.2. Discussion

The results of Condition 3 suggest that the PCR depends only on participants' intention to stay in synchrony, not on their expectations regarding the nature of the perturbations. The fact that 50% of the perturbations were of the EOS type, for which phase correction is a non-optimal strategy, did not reduce participants' ability to react optimally to PS perturbations. For these PSs, the PCRs and the subsequent

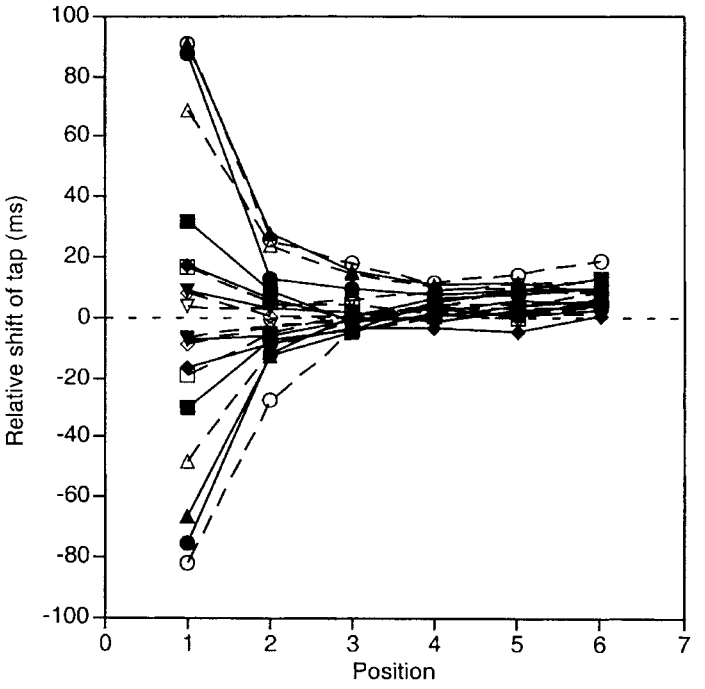

Fig. 9. Average phase correction functions (relative shift of tap as a function of position) in Condition 3 for all EOS magnitudes (not identified).

phase correction were highly similar to those observed in Condition 1, where only PSs occurred.

As a consequence of participants' successful adoption of the PS strategy, PCRs to EOSs were much larger than in Condition 2, where only EOSs occurred and the EOS strategy was followed. Following these large PCRs, however, phase correction was more rapid initially than the linear phase correction model would predict on the basis of the slope of the PCR function. Both this time course of phase correction and the sigmoid shape of the PCR function indicate significant nonlinearities in the phase correction process.

6. Condition 4: Event onset shifts and phase shifts mixed (EOS strategy)

In this condition, sequences containing PSs and EOSs occurred randomly intermixed, and participants were instructed not to react to any perturbations. This is the EOS strategy, which is appropriate for EOSs but not for PSs. As in Condition 3, the PCRs to the two types of perturbation had to be identical because PSs and EOSs do not differ initially. Therefore, PCRs were again averaged across PSs and EOSs. The main question of interest was whether the resulting PCR function would be equal to that for EOSs in Condition 2, or whether the occurrence of PSs in the same condition would reduce participants' ability to inhibit their PCR to the first shifted tone.

Condition 4 differed from Condition 3 in that the phase correction following the PCR was expected to be affected as well. In Condition 3, the time course of phase correction was fairly normal because participants intended to stay in synchrony. In Condition 4, participants did not intend to stay in synchrony but rather intended to continue tapping at a regular tempo following any perturbation. Successful application of this strategy would lead to a perpetuation of the relative shift associated with the PCR. In the case of EOSs, this relative shift would be small, and it was expected that the taps would automatically gravitate back to the pre-perturbation relative asynchrony (i.e., zero). In other words, phase correction would probably occur without participants' awareness. The same was expected to happen following PCRs to small PSs, except that the taps would shift in the opposite direction (cf. Fig. 1(c) and (d)). With large PSs, however, it was considered possible that participants would successfully maintain the relative shift of the PCR and thus tap out of synchrony with the remainder of the sequence. Thus, Condition 4 tested not only participants' ability to inhibit their PCRs but also their ability to resist subsequent phase correction.

6.1. Results

Fig. 10(a) shows the average PCRs (EOS + PS) as a function of perturbation magnitude, with single standard-error bars. For comparison, the PCR function for EOSs in Condition 2 (EOS only) is also shown. The two functions are quite similar; a marginally significant difference is present at one Δ value (+150 milliseconds). Thus, as in Condition 3, the mixing of the two perturbation types had little effect on the PCRs. Figs. 10(b), however, shows that trial-to-trial variability as well as individual differences in variability were greater in Condition 4 than in Condition 2, especially for negative perturbations.

Individual differences in PCR functions can be seen in Fig. 6 (open circles). The majority of participants showed significant differences between Conditions 2 and 4, but the nature and direction of these differences were idiosyncratic. For all but two participants, the strongly nonlinear function had an approximately linear central portion; in two cases (B.V., B.R.), however, the linearity was violated by an upturn on the negative side. Table 2 lists the slopes of regression lines fitted to the whole function and to the central portion between −50 and +50 milliseconds. These slopes were quite similar to those obtained in Condition 2, and 9 out of 10 participants showed a steeper central than overall slope, $t(9) = 5.79$, $p < 0.001$. The correlations between Conditions 2 and 4 were 0.71 (overall slopes, $d.f. = 8$, $p < 0.05$) and 0.84 (central slopes, $d.f. = 8$, $p < 0.01$), which suggests greater reliability of unintended than of intended PCRs (for which each correlation was only 0.55).

Rather than plotting average phase correction functions (as in Figs. 4, 7, and 9), which would have been highly variable and unrepresentative in this condition, the analysis of phase correction following the PCR focused on the relative shift of the 6th (the last recorded) tap following a perturbation. Assuming total success in following the EOS strategy, the expected relative shift of the 6th tap was the average PCR (Fig. 10(a)), regardless of the type of perturbation. Fig. 11(a) shows the actual relative shifts of the 6th tap following EOSs (EOS strategy). Their pattern did not

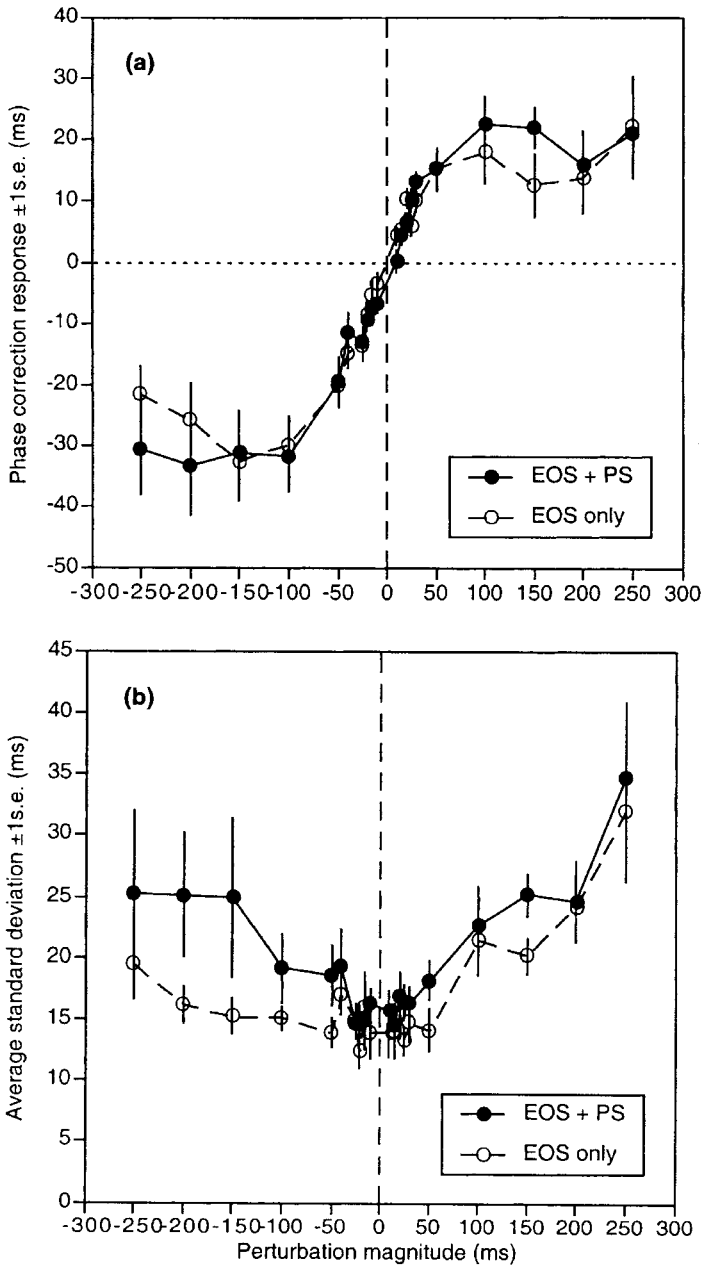

Fig. 10. (a) Average phase correction responses as a function of perturbation magnitude in Condition 4 (EOS + PS), with single standard error bars. The results of Condition 2 (EOS only, from Fig. 5(a)) are shown for comparison; (b) the corresponding average standard deviations, with single standard error bars.

resemble at all that of the PCR. It was somewhat erratic and unrelated to EOS magnitude (solid regression line, slope = 0.007). For comparison, the analogous results from Condition 3 are shown (PS strategy). Here, where phase correction was intended, the expected relative shift was zero for all EOS magnitudes, to the extent that phase correction was complete within six taps. Indeed, there was little relation to

EOS magnitude (dashed regression line, slope = 0.010), only some positive drift (i.e., a positive zero intercept), as noted earlier. Compared to Condition 3, the present condition showed more between-participant variability but no positive drift (i.e., a more stable tapping tempo). Thus, participants' intention not to synchronize with sequences following a PS had some impact on their phase correction following EOSs as well, but mainly in the form of increased variability. Participants did correct the PCR elicited by an EOS.[9]

The relative shifts of the 6th taps following PSs are shown in Fig. 11(b) (EOS strategy), together with the results for PSs in Condition 3 (PS strategy). The relative shifts in Condition 3 follow a straight line with a slope close to 1, except for the accelerating strategy for PSs of +250 milliseconds (isolated data point in the lower right-hand corner). This indicates complete phase correction; note also the tiny standard errors (smaller than circle diameters). If participants had been able to follow the EOS strategy in Condition 4, they should have continued the relative shifts of the PCRs (Fig. 10(a)). It is clear that they did not. Their taps were attracted to the sequence tones, especially on the negative side (i.e., the negative shifts were much larger than those of the PCR), and between-participant variability was huge.

To get an accurate impression of participants' behavior, it is necessary to look at the individual data. They are presented in Fig. 12 in the form of scatter plots (5 trials per Δ value). Four participants (C.P., E.P., M.K., N.T.) were rather unsuccessful in applying the EOS strategy to PSs. Their taps were strongly attracted to the phase-shifted tones, especially after negative PSs, and thus their data points for the 6th tap fell close to the main diagonal. After large positive PSs, the taps of 3 of these 4 participants followed the accelerating strategy and thus ended up in phase with the sequence again (lower right-hand corner of the graph); only a few trials on the positive side showed evidence of disengagement from the sequence. The other 6 participants were more successful: S.V. only after positive PSs, A.N. and B.B. only after large PSs, and E.W., B.V., and B.R. pretty much across the whole range. However, the trial-to-trial variability was enormous, which means that the relative phase of the taps was very unstable. In no case was there evidence that the relative shift of the PCR (Fig. 6) was maintained, and this implies considerable drift between the 1st and 6th taps following a PS.

6.2. Discussion

The results of Condition 4, in conjunction with those of Condition 3, suggest that the PCR is determined by participants' intentions but not by the likelihood of occurrence of one or the other type of perturbation. However, the variability of the PCRs was somewhat greater in Condition 4 than in Condition 2 (EOSs only), and the phase correction following EOSs was more variable in Condition 4 than in Condition 3, even though the response strategy of Condition 4 was initially more appropriate for EOSs (i.e., led to smaller PCRs) than the response strategy of

[9] It is not clear what to make of the apparent U-shape of the function in the vicinity of zero.

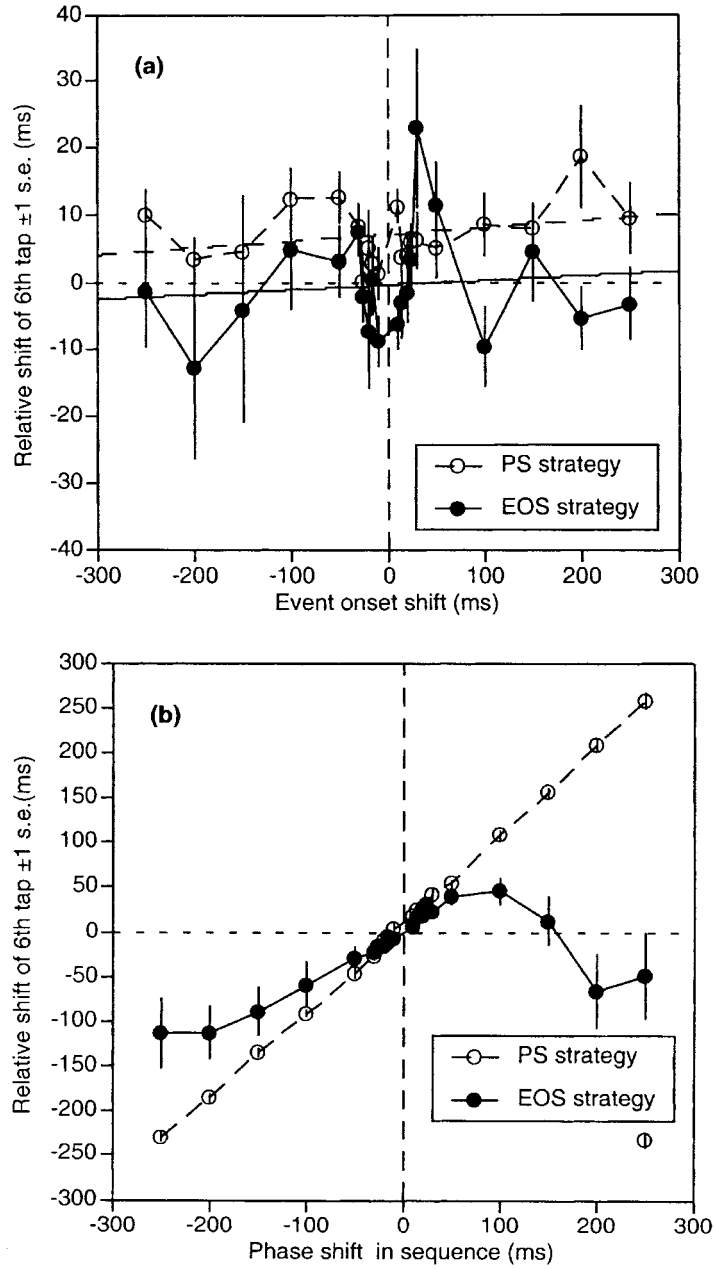

Fig. 11. Average shifts of the 6th tap following a perturbation in Conditions 3 (PS strategy) and 4 (EOS strategy), as a function of perturbation magnitude: (a) taps following EOSs; (b) taps following PSs.

Condition 3. This suggests that the intended disengagement from phase-shifted sequences caused greater variability throughout.

The results for PSs demonstrate that an auditory sequence is a strong attractor towards which taps tend to gravitate. The relative shift of the 6th tap following a PS probably does not represent a stable state. If tapping had continued, even stron-

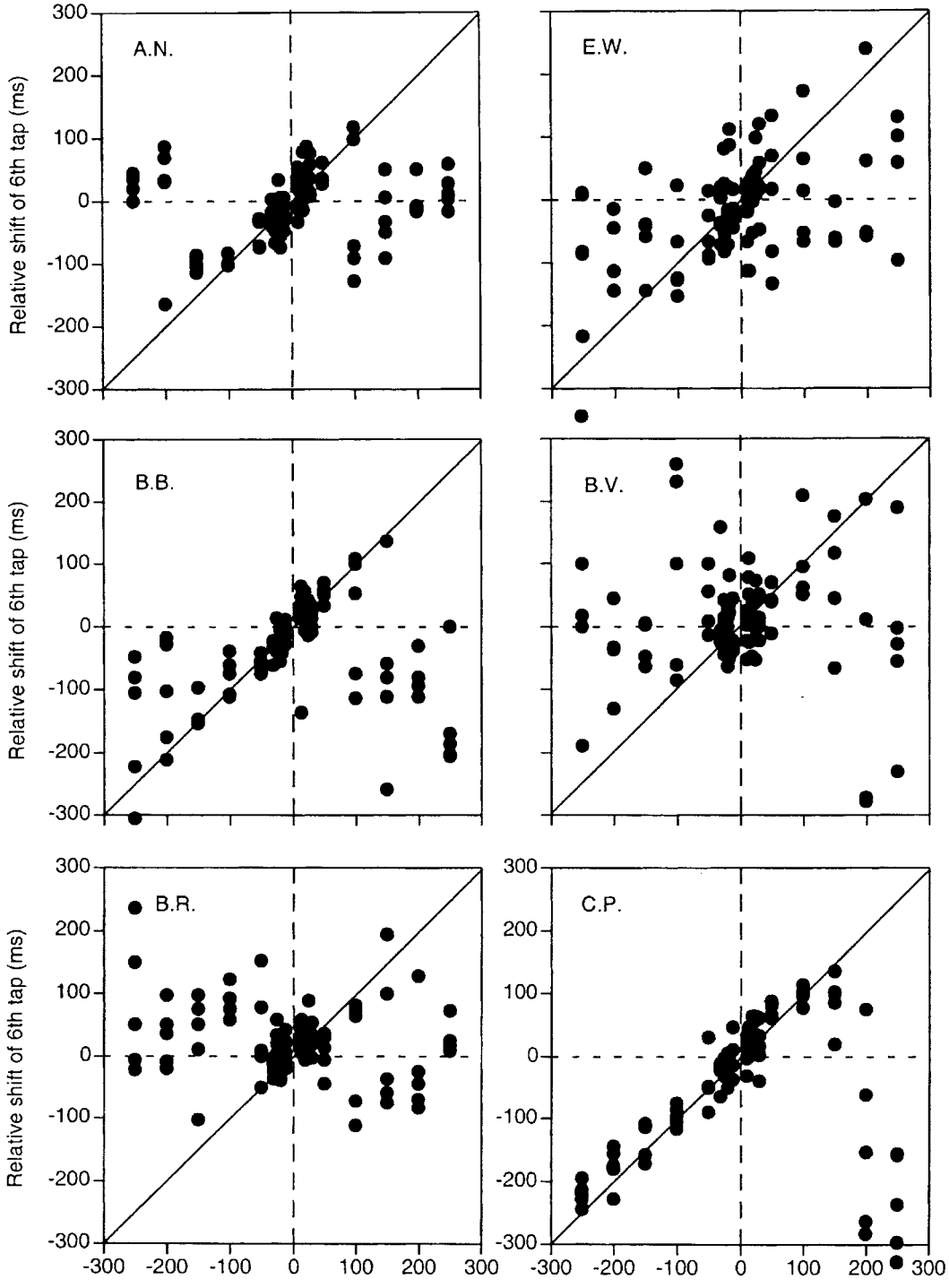

Fig. 12. Individual participant data for Condition 4. Relative shift of the 6th tap following a PS in the sequence, as a function of PS magnitude.

ger attraction might have been observed at a later point. The attraction seemed to be stronger after negative PSs than after positive PSs, though in part this was due to the

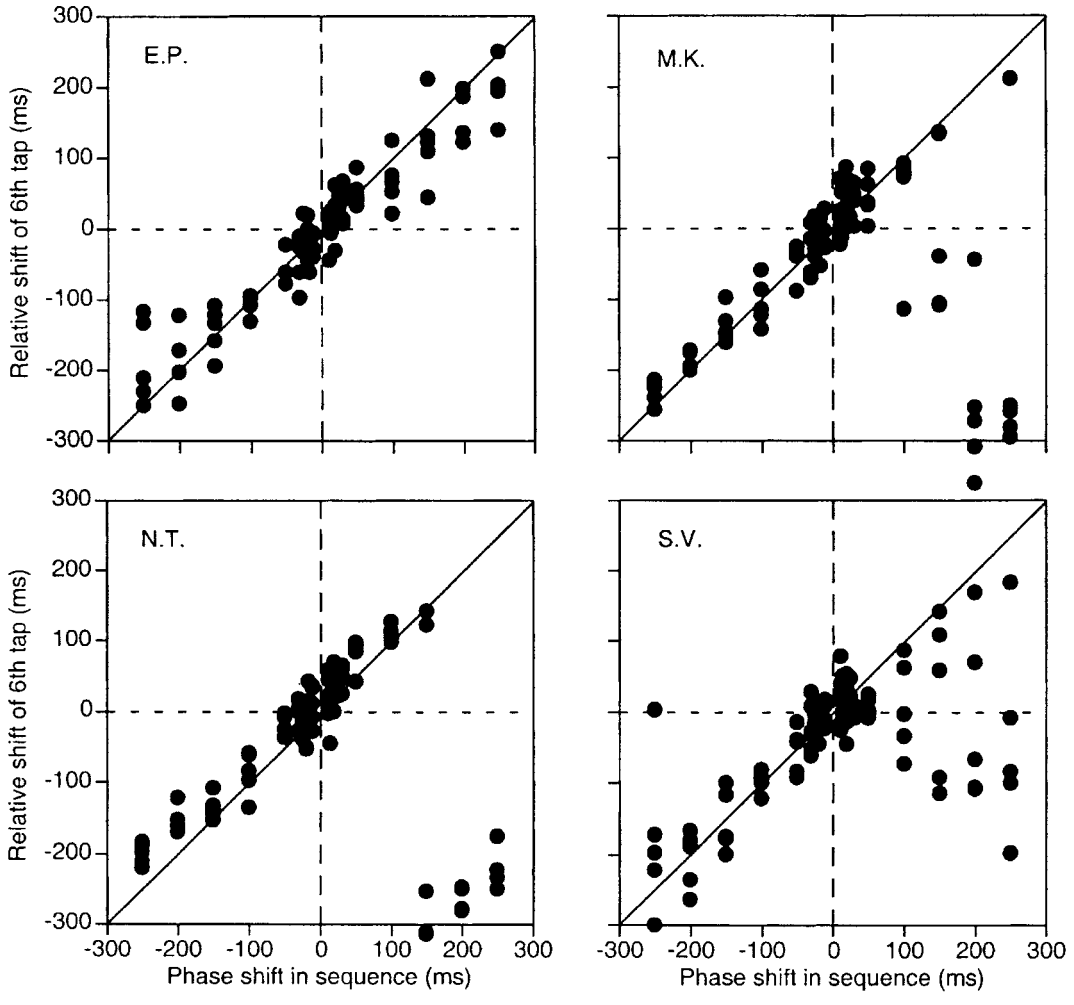

Fig. 12 (*continued*)

presence of two competing behaviors after large positive PSs. Those participants who managed to stay out of synchrony following PSs showed large trial-to-trial variability. The intended disengagement from the sequence evidently made the sequence unavailable as an external reference for maintaining a particular phase relationship.

7. General discussion

7.1. Implications for models of phase correction

The main purpose of this study was to examine in a qualitative way the generality of the linear phase correction model proposed by Mates (1994a,b), Pressing (1998, 1999), and Vorberg and colleagues (Semjen et al., 2000; Vorberg & Schulze, in press; Vorberg & Wing, 1996). As pointed out in Section 1, this model was developed to

account for synchronization with isochronous sequences, though in principle it can predict responses to all kinds of perturbation in a sequence. One assumption of the model is that the phase correction parameter α is independent of the magnitude of the relative asynchrony, so that the PCR is predicted to be a linear function of this magnitude, at least as long as phase correction is intended. The present results (together with those of Repp, 2002a) show that this linearity assumption is justified only within a small range of perturbation magnitudes, approximately $\pm 10\%$ of the sequence period (perhaps up to $\pm 15\%$). When perturbations exceed this range, phase correction becomes less effective (i.e., α decreases). Although only a single IOI duration was investigated here, the observed nonlinearities are likely to hold for other IOI durations as well.

A more general model of phase correction thus will have to include a nonlinear control function. The present average data suggest a vaguely sigmoid shape for that function, similar to that envisioned by Engbert et al. (1997), although the data points for the largest perturbations ($\pm 50\%$ of the sequence period) were not quite in line with such a function. On the positive branch of the PCR function for PSs, this deviation could be attributed to the observed split between decelerating and accelerating correction strategies. However, this explanation cannot account for the symmetric findings on the negative branch of the function because no alternative correction strategy was observed there. Thus, the precise shape of the average PCR function may be more complex than a simple sigmoid shape.

The observed PCR function seems inconsistent with a sinusoidal phase coupling function (Large & Jones, 1999; Large & Kolen, 1994). Such a function predicts increases in the PCR to perturbations of up to $\pm 25\%$ of the sequence period, followed by a decrease leading to zero response at $\pm 50\%$. This model may be appropriate in a beat-tracking algorithm, where a relative shift by half a cycle is to be avoided because such large deviations in a sequence usually signify subdivision, not shift, of a beat. In a synchronization task with intended phase correction, however, shifts of any magnitude require an adaptive response. It is possible that elaborations of the sinusoidal phase coupling model that include integration over time would be more consistent with the present findings. However, the emergence of an alternative correction strategy as phase delays approach half the sequence period is also incompatible with a sinusoidal control function because such a function is a continuous function of phase. A sigmoid function can accommodate the data more readily because it is restricted to one phase cycle and therefore would exhibit a discontinuity from one cycle to the next.

In any case, it may be too simplistic to assume a single kind of control function for everybody. Different individuals in this study showed different and often asymmetric PCR functions. It will take additional theoretical effort to devise a model that can accommodate this individual variety, which often tends to be swept under the rug in psychological research. It must also be admitted, however, that 10 observations per data point were probably not sufficient to determine the precise shape of the PCR function for each individual.

A model of phase correction must also account for the time course of phase correction following the PCR. The observed functions generally had a negatively

accelerated curvilinear shape, which is consistent with the linear model. However, they did not always match the exponential function predicted by that model. Phase correction following large perturbations seemed to be faster than predicted immediately following the PCR, even though the reduced PCR suggested a smaller α. It seemed as if the second tap compensated for the sluggish initial response. In the case of PSs, this compensation could be attributed to second-order error correction (Pressing, 1998; Semjen et al., 1998); that is, the tap in position 2 could still have corrected for part of the relative asynchrony generated by the perturbation in position 0. However, a similar phenomenon was observed following EOSs, where it cannot be attributed to second-order error correction because the relative asynchrony generated by the perturbation has the opposite sign of the relative asynchrony generated by the PCR (see Fig. 1(d)). It should be noted here that a function resembling an exponential function can result from averaging functions of quite different shapes, but that deviations from an exponential function probably indicate that some of the individual functions going into an average function exhibit deviations as well. Thus the nonlinearity following a large perturbation seems to extend beyond the PCR.

7.2. Automaticity versus voluntary control of phase correction

The present results replicate the earlier finding (Repp, 2002a) that phase correction is both automatic and under voluntary control. Phase correction is automatic in the sense that a PCR to a phase perturbation is difficult to avoid. It is under voluntary control in that it can be reduced substantially by intending not to react to perturbations. The average PCR function for EOSs seemed to be a "squashed" version of the sigmoid function for PSs, approaching asymptotes approximately where the latter function began to deviate from linearity. Thus it seems possible that these two nonlinearities have a common origin.

In a previous publication (Repp, 2001a), it was hypothesized that the typically gradual nature of phase correction results from a dynamic conflict between "motor persistence" (implying no phase correction) and event-based phase resetting (implying perfect phase correction) (cf. Hary & Moore, 1985, 1987a).[10] The PS strategy maximizes phase resetting, as much as motor persistence allows. The EOS strategy maximizes motor persistence, as much as phase resetting allows. The two strategies thus probably require focusing attention on the auditory event sequence and on the motor activity, respectively. A shift in attention alone, however, is probably not sufficient to account for the relative success of the EOS strategy. The intention not to react implies active inhibition of the process of phase correction; in other words, an active decoupling of the motor activity from the external sensory reference. Thus, intentions can substantially affect the behavioral dynamics in sen-

[10] These competing processes can be seen as being closely related to the "maintenance tendency" and the "magnet effect," respectively, discussed in the context of intersegmental coordination by Von Holst (1937/1973), Amazeen, Amazeen, and Turvey (1998), and Riley, Santana, and Turvey (2001).

sorimotor synchronization, as is the case in other coordinative activities (see, e.g., Kelso, 1995, Chapter 5).

A new finding contributed by the present study is that expectations about the nature of the perturbations play no significant role in the strategic control over the PCR. In carrying out either the PS or the EOS strategy, it did not matter that the strategy was inappropriate for half of the perturbations. This identifies the strategies as intentional ones, rather than as subconscious adaptive processes that are passively driven by the probabilities of perturbation types in an experiment.

Another new finding is that at least some participants carrying out the EOS strategy were able to avoid phase correction and synchronization following the initial PCR to a PS (Condition 4). This success, however, came at the price of high variability. This instability indicates the absence of any internally generated reference with regard to phase; only the external sequence could provide stability. Since the taps did not make any sound, no auditory rhythmic pattern was produced that could have served as a reference (Repp, 2001a; Semjen & Ivry, 2001).[11] It seems that participants were unable to extrapolate perceptually the pre-perturbation relative phase of their taps (or that of the sequence) through and beyond a perturbation in the sequence. This is consistent with results of a recent experiment (Repp, 2002b) in which it was shown that phase correction after a PCR to an EOS does not occur during a silent gap following the EOS in the sequence; rather, it is delayed until the sequence continues. In other words, relative phase seems to be psychologically undefined in the absence of an external reference, as it is in physical systems. To the extent that participants were able to disregard the sequence in Condition 4, they successfully deprived themselves of the reference that is needed for the maintenance of relative phase, and this accounts for the high variability of their behavior.

In summary, this study provided empirical data relevant to models of sensorimotor synchronization which make a priori assumptions about the shape of the error correction function. Linearity was shown to hold for small errors, but nonlinearity was confirmed over a large range of asynchronies. Moreover, participants' intentions regarding error correction substantially altered the error correction function, especially its degree of nonlinearity. Accurate models of synchronization behavior will have to take these findings into account.

Acknowledgements

This research was supported by NIH grant MH-51230. The author is grateful to Yoko Hoshi for assistance, and to Edward Large, Amandine Penel, and two anonymous reviewers for helpful comments on the manuscript.

[11] As mentioned earlier, some participants (E.W., B.B., N.T.) struck the response key hard enough to produce an audible impact sound. While E.W. and B.B. were fairly successful with the EOS strategy for PSs in Condition 4, N.T. was not (see Fig. 12).

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