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Adaptation to tempo changes in sensorimotor synchronization: Effects of intention, attention, and awareness

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Adaptation to tempo changes in sensorimotor synchronization is hypothesized to rest on two processes, one (phase correction) being largely automatic and the other (period correction) requiring conscious awareness and attention. In this study, participants tapped their finger in synchrony with auditory sequences containing a tempo change and continued tapping after sequence termination. Their intention to adapt or not to adapt to the tempo change was manipulated through instructions, their attentional resources were varied by introducing a concurrent secondary task (mental arithmetic), and their awareness of the tempo changes was assessed through perceptual judgements. As predicted, period correction was found to be strongly dependent on all three variables, whereas phase correction depended only on intention.

Sensorimotor synchronization is of fundamental importance in music performance, dance, and other rhythmic activities. In the laboratory, it is studied most conveniently by asking people to tap their finger in synchrony with an auditory sequence (e.g., tones). Motor activity exhibits temporal variability, which leads to asynchronies between taps and sequence tones. Maintenance of approximate synchrony requires error correction based on sensory information about the asynchronies (but see Aschersleben, Stenneken, Cole, & Prinz, 2002, for an exceptional case of synchronization in the absence of sensory feedback). Without error correction, temporal variance would accumulate and inevitably lead to phase drift of the taps relative to the auditory sequence (Vorberg & Wing, 1996).

Viewed from a dynamic systems perspective, sensorimotor synchronization is a form of entrainment of one oscillatory process (motor) by another (perceptual), as a consequence of unilateral coupling between them (Pikovsky, Rosenblum, & Kurths, 2001; Wimmers, Beek, & van Wieringen, 1992). The parameter of coupling strength in such a continuous-time model is analogous to the parameter(s) governing the effectiveness of error correction in a discrete-time

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control equation (Pressing, 1999; Vorberg & Schulze, 2002). Because of the discrete nature of finger taps, the discrete approach has been predominant in studies of finger tapping.

Synchronization with an isochronous sequence (such as that produced by a metronome) requires only *phase correction.* Because the asynchronies are relatively small, even inherently nonlinear dynamics can be modelled as a locally linear process, and a linear autoregressive model of phase correction (proposed by several authors, e.g., Mates, 1994a; Pressing, 1998; Vorberg & Wing, 1996) has indeed been quite successful in accounting for the time series properties of both asynchronies and intertap intervals (ITIs; Semjen, Schulze, & Vorberg, 2000; Vorberg & Schulze, 2002). According to that model (see Appendix), the intended temporal placement of each tap (and hence each intended ITI) is adjusted by a fixed proportion of the perceived asynchrony associated with the immediately preceding tap. In some circumstances, especially at fast rates, the two most recent asynchronies seem to be taken into account (Pressing, 1998; Semjen et al., 2000). The linear phase correction model has also been supported by data showing that, following a small phase perturbation in an otherwise isochronous sequence, the average shift of the next tap (relative to its expected time of occurrence in the absence of a perturbation) increases linearly with perturbation magnitude (Repp, 2001a, 2002c; Repp & Penel, 2002). This shift has been termed the *phase correction response* (PCR). Only when perturbations larger than 10% of the sequence interonset interval (IOI) are introduced does the function relating the average PCR to perturbation magnitude begin to exhibit nonlinearities (Repp, 2002c), which reveals the essentially nonlinear nature of the underlying dynamics.

Phase correction appears to be largely an automatic process. It generally occurs without participants' awareness, and it is not limited by the perceptual detection thresholds for either perturbations or asynchronies, being just as effective below the detection threshold as above it (Repp, 2000, 2001a; Repp & Penel, 2002; Thaut, Tian, & Azimi-Sadjadi, 1998). Because awareness of a phase perturbation does not make phase correction more effective, it also seems likely that the process does not require attention. However, phase correction is not entirely automatic because it is subject to voluntary control. If participants in a synchronization experiment are instructed not to react to phase perturbations in a sequence, their PCRs to large perturbations are greatly reduced, though not suppressed completely (Repp, 2002a, 2002c). For perturbations below the detection threshold, however, the PCR magnitude increases linearly with perturbation magnitude and does not seem to depend on participants' intentions. Thus, awareness of a perturbation seems to be required for intentional inhibition of phase correction.

When people synchronize rhythmic actions with a sequence that contains a change of tempo, a second error correction process, *period correction*, comes into play. It adjusts the period of an internal timekeeper or oscillatory process. Period correction has been investigated less thoroughly than phase correction. Mates (1994a, 1994b) proposed a two-process model that includes a linear autoregressive mechanism for period correction analogous to that for phase correction (see Appendix). The relevant sensory information is more complex, however: It is a difference between intervals, namely the discrepancy between the previous timekeeper period and the most recent sequence IOI. Figure 1 presents a schematic diagram of the two-process model (see caption for explanation). Its architecture bears obvious conceptual similarities to the well-known model of Wing and Kristofferson (1973; see also Ivry & Hazeltine, 1995; Vorberg & Wing, 1996), which distinguishes central and more peripheral sources of variability (loosely called timekeeper and motor variance, respectively) in rhythmic

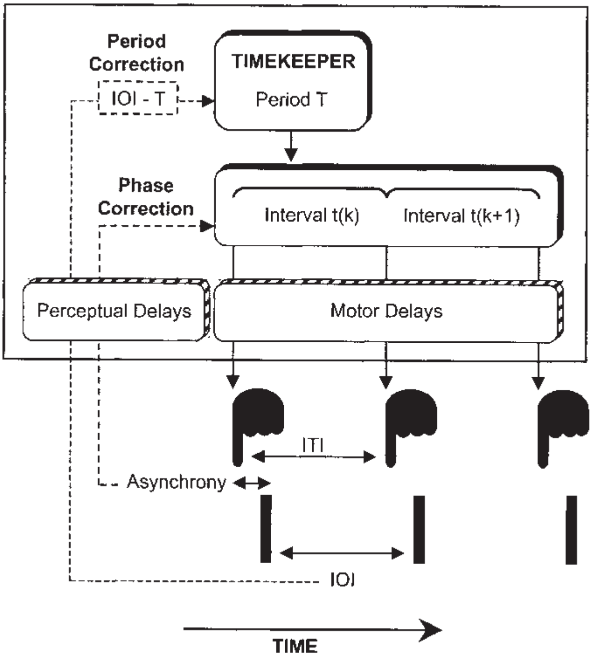

Figure 1. Schematic diagram of the two-process error correction model for sensorimotor synchronization (after Mates, 1994a). A central timekeeper with period T is assumed to control the intervals, t(k), t(k+1), . . ., between successive motor commands. The period T can be adjusted on the basis of perceived discrepancies between its duration and the tone interonset interval (IOI) in the sequence (*period correction*). The intervals t(k), t(k+1), . . ., can further be adjusted individually on the basis of registered asynchronies between taps and tones (*phase correction*). The frame indicates internal processes; only intertap intervals (ITIs) and asynchronies are directly observable. They are affected by both period correction and phase correction.

movement. Period correction and phase correction may likewise be seen as central (cognitive) and more peripheral (sensorimotor) control processes, respectively, within the central nervous system. The crucial assumption of the two-process model is that phase correction and period correction are independent of each other, so that their behavioural effects are additive.

Although a change in the manifest tapping tempo (the ITIs) can be achieved by adjusting each successive tap on the basis of the preceding asynchrony—that is, through phase correction alone—it makes sense to assume that the period of an internal timekeeper or oscillator is changed if a different tempo is intended. During synchronization, however, it is difficult to tell whether and to what extent a participant's internal period has changed because the behavioural effects of period correction are indistinguishable from those of phase correction (Repp, 2001a): Both processes affect asynchronies and ITIs in similar ways. To estimate period correction, Repp (2001b) made use of the synchronization–continuation paradigm (Stevens, 1886; Wing & Kristofferson, 1973): Sequences containing a tempo change were terminated at various points after the tempo change, and participants were required to continue tapping at the new sequence tempo. Because phase correction is inoperative in the absence of an external reference (Repp, 2002b), the ITIs produced during continuation tapping were assumed to provide a direct estimate of the internal timekeeper period achieved by the end of the sequence. This estimate increased in a roughly exponential (negatively accelerated) fashion with the number of sequence IOIs following the tempo change, as predicted by the linear model of period correction.

Repp (2001b) also asked participants to report whether or not they had detected a tempo change in each sequence. When the continuation ITIs were analysed contingent on these detection responses, period correction was found to be significantly greater when a tempo change had been detected than when it had not been detected. This suggested that period correction is facilitated by conscious awareness of a tempo change, in contrast to phase correction, which is not facilitated by awareness of a phase perturbation (Repp, 2000). Consistent with this interpretation, a difference in the time course of overt adaptation to small and large tempo changes during synchronization (first described by Thaut, Miller, & Schauer, 1998) was found to coincide with the detection threshold for a tempo change: Detected tempo changes were followed by initial overcorrection of the ITI relative to the new sequence IOI and subsequent adaptation, whereas undetected tempo changes were followed by smooth adaptation to the new IOI without overshoot. The overshoot was attributed to the simultaneous and independent engagement of period correction and phase correction processes, whereas the smooth adaptation was considered to reflect the operation of phase correction only.

Thus, phase correction and period correction seem to represent independent processes of largely automatic action control and of intentional cognitive control, respectively. Analogous processes in the visual control of action are currently the subject of extensive research and discussion (see, e.g., Milner & Goodale, 1995; Rossetti & Pisella, 2002). The present study and its predecessors pursue this dichotomy in the context of auditory action control. Whereas the previous work of Repp (2001b) had focused on the role of awareness in period correction, in the present experiment we investigated the effects of two additional variables, intention and attention, on both phase correction and period correction.

Intention was varied by instructing participants either to adapt or not to adapt to tempo changes. In the adaptive condition, participants were required to maintain synchrony with the auditory sequence and to continue to tap at the final (new) sequence tempo after sequence termination, as in Repp (2001b). In the novel nonadaptive condition, by contrast, participants were told to tap at the initial sequence tempo, both after a tempo change (which implies poor synchronization) and after the sequence had ended. These instructions were expected to affect period correction more than phase correction. Specifically, if period correction is consciously controlled, then instructions not to adapt should eliminate period correction completely. By contrast, phase correction during synchronization would be reduced but not suppressed entirely, as has been shown previously in the context of phase perturbations (Repp, 2002a). Thus, we expected to find some involuntary adaptation to the new tempo during synchronization (due to phase correction), but not during continuation tapping.

Attention was varied by comparing a single-task with a dual-task condition. Actually, the single-task condition consisted of three related tasks: synchronization, continuation tapping, and perceptual judgement of tempo changes. However, the dual-task condition included in addition a mental arithmetic task that had to be carried out at the same time as synchronization. We chose mental arithmetic because it is intentional, effortful, and resource demanding. Our hypothesis was that this diversion of attention would selectively affect intentional period correction. A large body of research has demonstrated that attentional resources are required when making duration judgements or producing time intervals of a prespecified duration (see

Brown, 1997, for a review). This research suggests that attention plays a role in generating a referent periodicity with which to measure the passage of time (an internally driven process), but little is known about the attentional requirements of maintaining synchrony with a referent periodicity in the environment (an externally driven process). In the synchronization task, diversion of attention could affect period correction either directly or indirectly, via a decrease in the detectability (hence awareness) of tempo changes. The direct effect can be assessed by analysing the data contingent on participants' detection responses and finding that attention has an effect that is independent of awareness. We also expected to replicate the effect of awareness on intentional period correction (Repp, 2001b). By contrast, intentional phase correction was expected to be unaffected by variations in either attention or awareness.

Effects of attention and awareness may also occur in the nonadaptive intention condition, though we were less confident of our predictions here. To the extent that the intentional suppression of either phase correction or period correction requires attentional resources, we should see evidence of recovery when dual-task demands are introduced. Because phase correction is thought to be more automatic than period correction and hence more difficult to suppress, we tentatively predicted greater recovery for phase correction than for period correction. Furthermore, if active suppression of either process is facilitated by awareness of a tempo change, then lack of awareness likewise should be associated with recovery. Indeed, it may be that intentional suppression of either process is entirely ineffective in the absence of awareness of a tempo change. The effect of the attentional manipulation may likewise depend on awareness, perhaps occurring only when a tempo change has been detected.

EXPERIMENT

Methods

Participants

The 10 participants included 4 women and 4 men who regularly performed in various finger tapping experiments and were paid for their services, as well as both authors. Ages ranged from 18 to 31 years, except for the first author and another participant who were 57. All had substantial musical training (9 or more years of study of one or more instruments) and were right-handed.

Materials

Auditory sequences were produced on a Roland RD-250s digital piano under control of a program written in MAX running on a Macintosh Quadra 660AV computer.[1] Each sequence consisted of 10 identical high-pitched digital piano tones (C8; 4176 Hz), which had a sharp attack (including a realistic "knock" representing the impact of the key on the key bed) and decayed within about 100 ms. Some sequences had a constant tempo and served as controls to assess participants' ability to continue tapping at a given tempo. These sequences had one of five constant IOI durations: 480, 490, 500, 510, and 520 ms. All other sequences started at the same tempo (IOI = 500 ms) and contained an abrupt "step change"

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[1] It is known from earlier measurements that the MAX software on this setup produces output that is 2.4% faster than specified and records input 2.4% slower than received. For convenience, all temporal specifications and data are reported here as they appeared in the MAX environment. To obtain the actual values, multiply by 0.976. Apart from this constant scaling factor, MAX was believed to be accurate within ±1 ms.

(Michon, 1967) to a new tempo preceding the last three IOIs. The IOI durations representing the new tempo were 475, 480, 485, 490, 495, 505, 510, 515, 520, and 525 ms. In other words, the changes in IOI duration ranged from –25 to +25 msec (–5% to +5%) in 5-ms (1%) increments. Each sequence was followed after a lengthy silent interval (equal to 12 times the final IOI of the sequence) by a single tone of lower pitch (E7), which served as the signal to stop continuation tapping. Altogether, there were 15 sequences (5 without tempo changes and 10 with tempo changes), which were arranged into 11 different randomizations (blocks). The first block served as practice.

Procedure

Participants sat in front of the Macintosh computer, listened to the sequences over Sennheiser HD540 II earphones at a comfortable intensity, and tapped on a Roland SPD-6 electronic percussion pad, which they held on their lap. The sensitivity of the pad was set to the manual (as opposed to drum-stick) mode. Participants tapped with the right index finger (in one case, with the middle finger). Some participants rested their hand on the pad and tapped by moving the index finger only; others preferred to tap "from above" by moving the wrist and/or elbow joints of the free arm. The impact of the finger on the rubber pad provided some direct auditory feedback (a thud), in proportion to the tapping force. (No digital sound output from the percussion pad was heard.) Participants started tapping with the third tone in each sequence.

Each condition of the experiment required a one-hour session. The order of the four conditions was the same for all participants. It followed the logic of increasing novelty (adaptive vs. non-adaptive) overall and increasing difficulty (single vs. dual tasks) within each intention condition. Successive sessions were typically one week apart. The same trial blocks were presented in all four conditions.

In the adaptive single-task condition (Session 1), participants had to carry out three tasks with each sequence: (1) to synchronize their taps with the sequence tones, adapting to any tempo change that might occur, (2) to continue tapping without interruption at the final tempo of the sequence after the sequence had ended, until they heard a lower pitch tone, and then (3) to report whether they had detected a tempo change in the sequence by pressing one of three keys on the computer keyboard, which were labelled "slowed down", "no change", and "speeded up", respectively. This response caused the next sequence to start 3 s later. No feedback about the correctness of the response was provided. Participants were informed that any tempo change would always occur three intervals before the end of a sequence. They were urged not to guess but to report their perceptual experience as truthfully as possible. It was pointed out that sequences could start at different tempi, but it was not mentioned that sequences starting at a nonstandard tempo (IOI ≠ 500 ms) never contained a tempo change. (The authors, naturally, were aware of this.)

The adaptive dual-task condition (Session 2) was identical, except for the added mental arithmetic task. This task required adding a random series of eight digits, each of which was either a 1 or a 2. (Thus, possible sums ranged from 8 to 16.) The digits appeared in a large font (10 mm high) inside a blank panel that occupied the right half of the computer screen. Each digit was displayed for 300 ms, and the next digit appeared in the same place. The appearance of each digit was synchronized with the sequence tones, starting with the third tone (i.e., when participants started tapping).[2] Participants had to remember the calculated sum as well as their perceptual judgement during continuation tapping. After

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[2] Random digit timing might have interfered with perception of the tone sequence or caused reflexive perturbations to tap timing, and isochronous digit timing might have provided a reference against which tempo changes in the tone sequence could be measured. Repp and Penel (2002) have shown that visual stimuli synchronous with tones have no effect on the variability of synchronized tapping, even if attention is focused on the visual modality. Also, temporal discrimination is much poorer in the visual modality, so that the tempo change in the digit sequence was not expected to facilitate the detection of the tempo change in the tone sequence. The digits had a longer duration than the tones as well as a distinct offset, but we do not believe that this had any effect on synchronization.

the signal to stop tapping had sounded, a small panel appeared on the computer screen, into which participants entered the sum, using the computer keyboard. Feedback in the form of the word "correct" or "incorrect" was subsequently displayed on the screen. Then participants entered their response concerning their perception of a tempo change in the sequence. Participants were asked to focus their attention on the arithmetic task, but without sacrificing accuracy in tapping. They were told that the purpose of the arithmetic task was to divert their attention from the tempo changes in the sequences, and that as a result they might hear fewer tempo changes than in the previous session. However, it was emphasized that they must report truthfully any tempo changes they did notice.

In the nonadaptive single-task condition (Session 3), participants were told not to adapt to any tempo change that might occur in the sequence—that is, to continue tapping at the initial tempo of the sequence, even though this would result in asynchronies—and also to continue tapping at the initial sequence tempo after the sequence had ended. In the nonadaptive dual-task condition (Session 4), the same instructions were given, and the arithmetic task was added.

Data analysis

We first examined the behavioural results in terms of the time course of adaptation of the ITIs to tempo changes. (We did not analyse the asynchronies.) In those data, the effects of phase correction and period correction were confounded during synchronization, but the ITIs of continuation tapping yielded a direct estimate of period correction (according to our assumptions). Subsequently, we fitted the linear two-process model to the data and obtained separate parameter estimates for phase correction and period correction, as described in more detail later. All analyses of variance (ANOVAs) reported below are of the repeated measures type.

Results

Arithmetic task

Although the mental arithmetic task seemed difficult initially because of the rapid presentation rate of the digits, most participants achieved good performance within two or three blocks of trials and showed no further improvement thereafter. However, no participant achieved consistently perfect scores, which indicates that the task was not trivial and that it continued to require attentional resources. The overall percentage of correct responses was 72.5% (73% in Session 2, 72% in Session 4). Two participants performed at a markedly lower level than the others; their average scores were 21% and 44% correct, respectively. The average scores of the other participants ranged from 69% to 92% correct.[3] A 2 × 10 ANOVA with the independent variables of session (or intention) and trial block showed no significant main effects. The interaction, reflecting lower scores in the initial blocks of Session 2, fell short of significance, $F(9, 81) = 5.5$, $p < .06$, presumably because of the large number of blocks over which performance was constant.

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[3] Some participants noticed that the sum could be calculated by merely keeping track of the number of ones (m) and then determining 16 – m, or some similar strategy. However, they said they had not actually used this strategy but had calculated the sum incrementally, in accord with our instruction to "add the digits".

Perceptual judgements

Figure 2 shows the average response percentages in the detection task as a function of step change magnitude for the two attention conditions (single vs. dual tasks), averaged over the two intention conditions. The scores for a step change of zero represent only the sequences with a constant IOI of 500 ms. (The other control sequences yielded similar or slightly lower percentages of "no change" responses.) Correct responses of "speeded up" or "slowed down" obviously increased with absolute step change magnitude, whereas "no change" responses decreased. The level of accuracy in the single-task condition is in agreement with results for tempo change detection reported in the literature (Drake & Botte, 1993; Friberg & Sundberg, 1995; Repp, 2001b). The percentages of correct "speeded up" and "slowed down" responses were averaged over the different step change magnitudes and subjected to a 2 × 2 × 2 ANOVA, with the independent variables of intention, attention, and direction of step change.

Correct response percentages were lower in the dual-task than in the single-task condition, $F(1, 9) = 27.2, p < .001$. Thus, the arithmetic task interfered with detection of tempo changes, as was fully expected. In addition, tempo decelerations were easier to detect than accelerations, $F(1, 9) = 5.8, p < .04$, as observed previously (Kuhn, 1974; Madsen, 1979; Repp, 2001b). The main effect of intention was nonsignificant, which indicates (somewhat surprisingly) that participants did not derive additional perceptual information from any increased asynchrony between their taps and the final sequence tones in the nonadaptive conditions. All interactions were likewise nonsignificant.

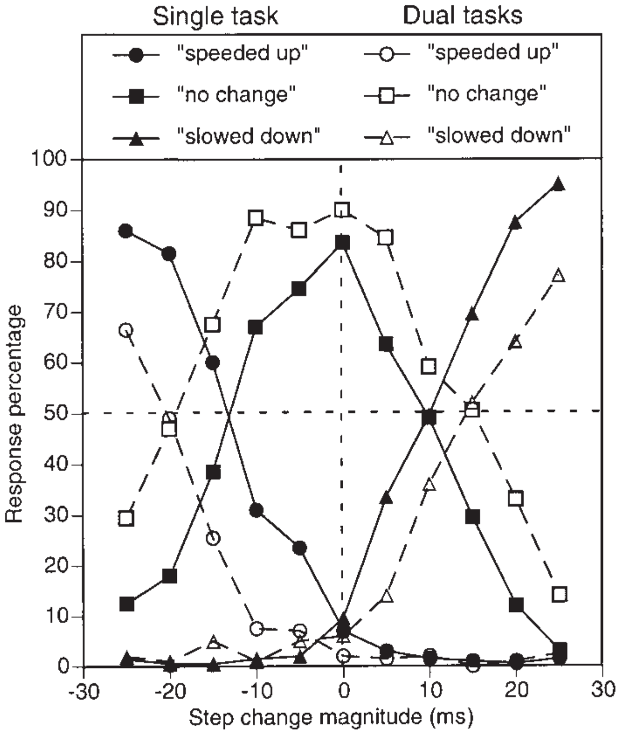


Figure 2. Average percentages of detection responses in single-task and dual-task conditions.

Measuring adaptation during synchronization and continuation tapping

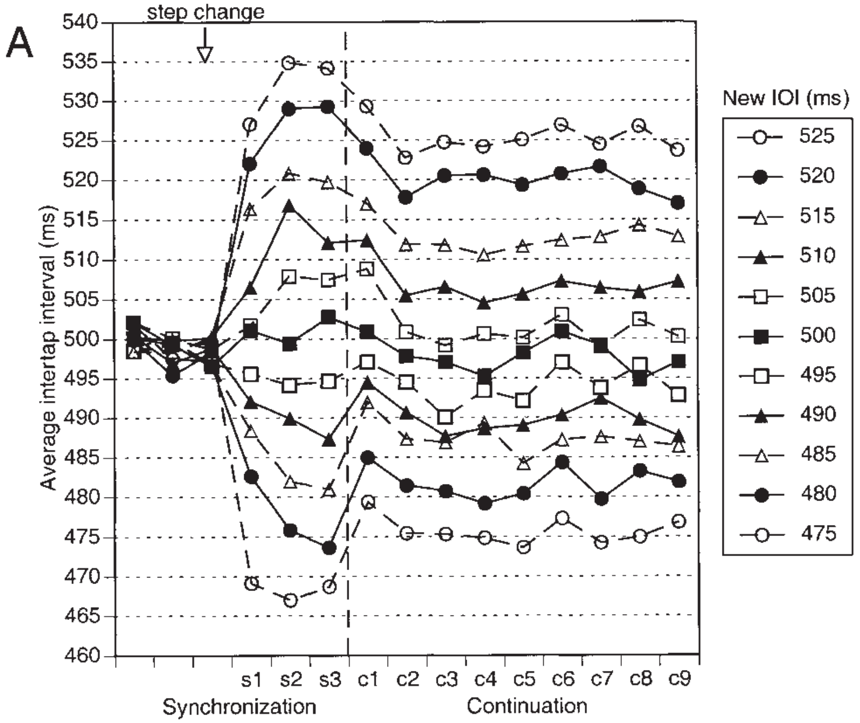
As an example of relatively unprocessed data, Figure 3A shows the average ITIs in the adaptive single-task condition. Only the last six synchronization ITIs and the first nine continuation ITIs are shown. It can be seen that the ITIs were initially close to 500 ms and then changed rapidly in response to the step change. Adaptation to a step change during synchronization was reflected in the ITIs labelled s1, s2, and s3, the last interval being the one initiated by the tap that coincided approximately with the last sequence tone. Interval s1 was expected to reflect both phase correction (i.e., the PCR; Repp, 2002a) and incipient period correction. Intervals s2 and s3 were expected to reflect increasing period correction in addition to constant phase correction, resulting in overcorrection in the case of the larger (usually detected) step changes. This overcorrection can be seen clearly in Figure 3A. The continuation ITIs (c1–c9) were considered to reflect the period correction achieved by the end of the sequence (s3), without any phase correction. The contraction of the range of average ITIs between intervals s3 and c1 (across the vertical dashed line in Figure 3A) is assumed to reflect the loss of the contribution of phase correction to ITI duration. It can be seen that there was little systematic drift during continuation tapping, except for a lengthened first ITI (c1), which seems to be a reaction to the end of the sequence. These findings are in close agreement with those of Repp (2001b).

Adaptation to the tempo change during synchronization was examined in each of the three positions labelled s1, s2, and s3. Adaptation (period correction) as reflected in continuation tapping was examined by computing the average of the first nine continuation ITIs, collectively labelled c. In each case, the ITI durations were plotted as a function of the final sequence IOI duration, and regression lines were fitted to the data, as illustrated in Figure 3B for the s3 and c data from Figure 3A. This analysis was performed for each individual participant's data in each condition after averaging the ITIs across repetitions of the same trial type. The slopes of the regression lines constitute the *adaptation indices* of interest, which are referred to as A(s1), A(s2), A(s3), and A(c), respectively. A slope of 1 indicates perfect adaptation, whereas a slope of 0 indicates no adaptation at all. A slope larger than 1 indicates overcorrection, whereas a slope smaller than 1 indicates undercorrection. A negative slope suggests a counteradaptive strategy. In Figure 3B, A(s3) is 1.32, which reflects overcorrection, whereas A(c) is 0.94, which indicates somewhat less than perfect continuation of the final sequence tempo (i.e., almost complete period correction). It may be noted that the A(c) function is slightly curvilinear, with a shallower slope in the middle than at the extremes. This is attributed to the predicted effect of detection (awareness) on period correction, as described below.

In the ANOVAs, the four adaptation indices were compared by means of three planned orthogonal contrasts: (1) synchronization (the average of s1, s2, and s3) vs. continuation (c); (2) the initial response (s1) vs. the average of s2 and s3; and (3) s2 vs. s3.

Control sequences

Control sequences had a constant IOI and were analysed separately. Their purpose was to assess participants' ability to continue tapping at a specified constant tempo, and so only A(c) was of interest. A 2 × 2 ANOVA on A(c) revealed no significant effects of either intention or attention. The average A(c) index was 0.99. Thus, on average, participants were quite accurate



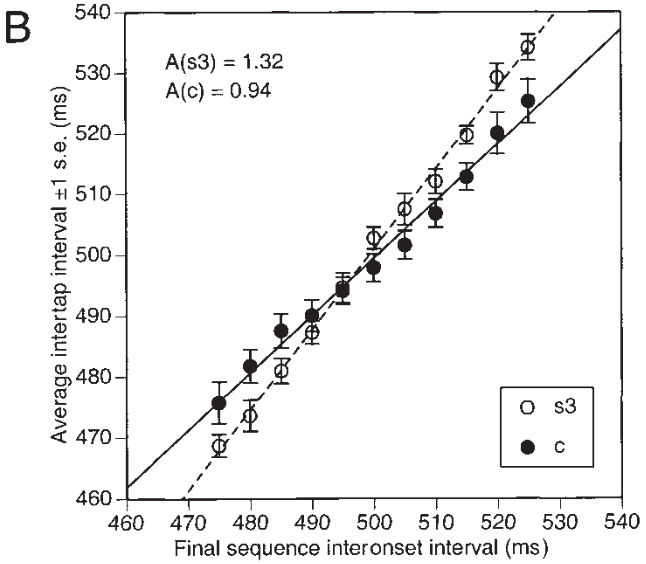


Figure 3. (A) Average intertap intervals in the adaptive single-task condition. IOI = interonset interval. (B) Data for positions s3 and c (average of c1 to c9; see Figure 3A) as a function of the final sequence interonset interval duration, with standard error bars and regression lines. The adaptation indices A(s3) and A(c) (slopes of the regression lines) are also shown.

in continuing to tap at a given tempo. Individual participants' A(c) indices ranged from 0.81 to 1.18 (averaged across the four experimental conditions), which suggests individual tendencies to reduce or exaggerate tempo differences. These control A(c) indices define individual upper limits for the A(c) indices in the step change sequences. In view of the almost perfect average index, however, it was not considered necessary to take these individual upper limits into account in subsequent analyses (as was done in Repp, 2001b). Control sequences with IOIs of 500 ms were also included in the following analyses of step change sequences.

Adaptive conditions

The average adaptation indices for the adaptive single-task (ST) and dual-task (DT) conditions are plotted in Figure 4A. The ANOVA on the synchronization–continuation contrast revealed a significant main effect of attention, $F(1, 9) = 38.2$, $p < .001$: Adaptation indices were generally lower in the dual-task than in the single-task condition. Thus, the arithmetic task clearly had an effect on performance, presumably by reducing period correction. Indeed, the interaction was also significant, $F(1, 9) = 18.7$, $p < .003$, reflecting a larger effect of attention in continuation than in synchronization. This is consistent with our hypothesis that only period correction requires attention: During synchronization, the effect of attention on period correction would be diluted by the presence of phase correction, if phase correction is unaffected by the attentional manipulation. Adaptation indices were generally larger in synchronization than in continuation, $F(1, 9) = 54.5$, $p < .001$, which we attribute to the presence of phase correction in addition to period correction during synchronization. The ANOVAs on the other two orthogonal contrasts showed that adaptation indices were larger in positions s2 and s3 (indicating overcorrection) than in position s1, $F(1, 9) = 44.2$, $p < .001$, but there was no significant difference between s2 and s3. The main effect of attention was significant in both contrasts, $F(1, 9) = 17.3$, $p < .003$, and $F(1, 9) = 21.0$, $p < .002$, respectively, showing that the arithmetic task had a reliable effect during synchronization, but the interaction effects were not significant.

Now we turn to an analysis of the same data that takes awareness of tempo changes into account. For each participant in each condition, we determined separate adaptation indices for trials in which a tempo change was detected and correctly identified (+d) and for trials in which no tempo change was detected (–d). Step change trials in which the tempo change was incorrectly identified and control trials (IOI = 500 ms) that received false-alarm responses were excluded. The ITIs were averaged over all qualifying trials for a given step change size before determining the slope of the regression line. Data points representing a single trial were excluded.[4]

The results are shown in Figure 4B. The ANOVAs on these data included the additional variable of awareness (+d vs. –d). (Effects that merely replicate the results shown in Figure 4A

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[4] Thus, the different step sizes were weighted equally in the detection-contingent regression analyses, even though they were represented by varying numbers of trials. The adaptation indices for –d trials were less reliable than those for +d trials because they were based on a limited range of data points (small step sizes) and therefore could easily be swayed by outliers. This resulted occasionally in unreasonable adaptation indices. For example, the large standard error of A(s1) for –d trials in the single-task condition (Figure 4B) was caused by two participants' values of –0.52 and 2.21, respectively, neither of which makes sense. Nevertheless, they were retained in the analysis because they did not seriously bias the average results.

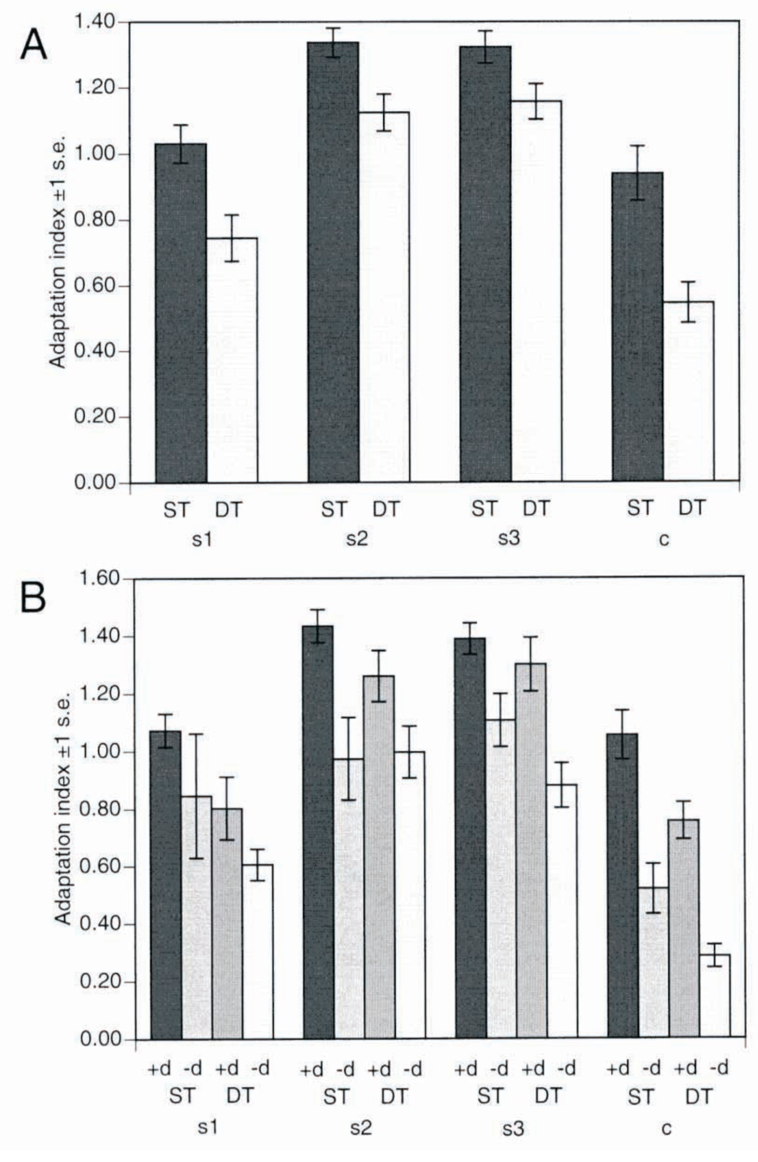

Figure 4. (A) Average adaptation indices with standard errors in the adaptive single-task (ST) and dual-task (DT) conditions. (B) The same data, analysed contingent on positive (+d) and negative (–d) detection responses.

will not be mentioned again.) In the ANOVA on the synchronization versus continuation contrast, awareness had a significant main effect, $F(1, 9) = 60.2, p < .001$: As predicted, adaptation indices were smaller when participants were unaware of a tempo change, presumably due to less effective period correction (Repp, 2001b). This interpretation is supported by a significant interaction, $F(1, 9) = 6.2, p < .04$, which reflects larger effects of awareness during continuation than during synchronization. In addition, a substantial main effect of attention persisted, $F(1, 9) = 22.5, p < .002$. Moreover, attention did not interact with awareness, $F(1, 9) = 3.0, p < .12$. This important finding shows that the effect of the arithmetic task was not mediated by its effect on detection of tempo changes (Figure 2). Rather, diminished attention affected adaptation directly, regardless of whether or not participants were aware of a tempo change. This suggests that the very process of period correction requires attentional resources.

The ANOVA on the s1 vs. s2 and s3 contrast also showed significant main effects of awareness, $F(1, 9) = 17.7, p < .003$, and attention, $F(1, 9) = 8.1, p < .02$, without any interaction. In the s2 vs. s3 contrast, the main effect of awareness was again significant, $F(1, 9) = 34.2, p < .001$, but that of attention fell short of significance, $F(1, 9) = 3.6, p < .10$, probably because of the increased variability of the detection-contingent adaptation indices. The effects of awareness and attention during synchronization are believed to be due to period correction only, but a more precise evaluation of this hypothesis requires model parameter estimation (see below).

Two details are worth noting. First, the right-most bar in Figure 4B shows that A(c) was significantly greater than zero even when tempo changes were not detected (–d), and attention was diverted (DT). This suggests that period correction, like phase correction, has an automatic component. Second, A(s1) in the same condition (–d, DT) approaches a value (0.6) that is fairly typical for phase correction in synchronization with sequences that are isochronous with IOI = 500 ms (e.g., Semjen et al., 2000) or contain small phase perturbations (Repp, 2000, 2002b), which suggests that period correction was minimal and that A(s1) represents the intentional PCR in that condition.

Nonadaptive conditions

The results of the nonadaptive conditions, first without taking awareness into account, are shown in Figure 5A. The difference between synchronization and continuation was significant, $F(1, 9) = 28.4, p < .001$: Whereas there was significant adaptation during synchronization, the A(c) indices were near zero. This is consistent with our hypothesis that period correction is under voluntary control, whereas phase correction has an automatic component that cannot be suppressed. Participants' intentions clearly had an effect during synchronization as well because these adaptation indices were substantially lower than those in the adaptive conditions (Figure 4A). To what extent this difference was due to the absence of period correction versus suppression of phase correction remains to be determined (see below). There was also a significant main effect of attention, $F(1, 9) = 12.1, p < .008$. Here, in contrast to the adaptive conditions, the adaptation indices were larger in the dual-task than in the single-task condition, which indicates that the intentional suppression of adaptive processes was less effective when attention was diverted. The interaction did not reach significance, $F(1, 9) = 2.6, p < .15$, although it is evident that the effect of attention was located mainly in s2 and s3. The interaction was significant, however, in the ANOVA on the s1 vs. s2 and s3 contrast, $F(1, 9) = 7.2, p < .03$, and nonsignificant in the s2 vs. s3 contrast. The main effect of attention was significant in both of these contrasts, $F(1, 9) = 10.2, p < .02$, and $F(1, 9) = 29.8, p < .001$, respectively. The strong effect of attention in positions s2 and s3 suggests that the suppression of phase correction after the initial PCR benefited from full attentional resources. It should be noted that this finding is not contrary to our hypothesis that phase correction does not require

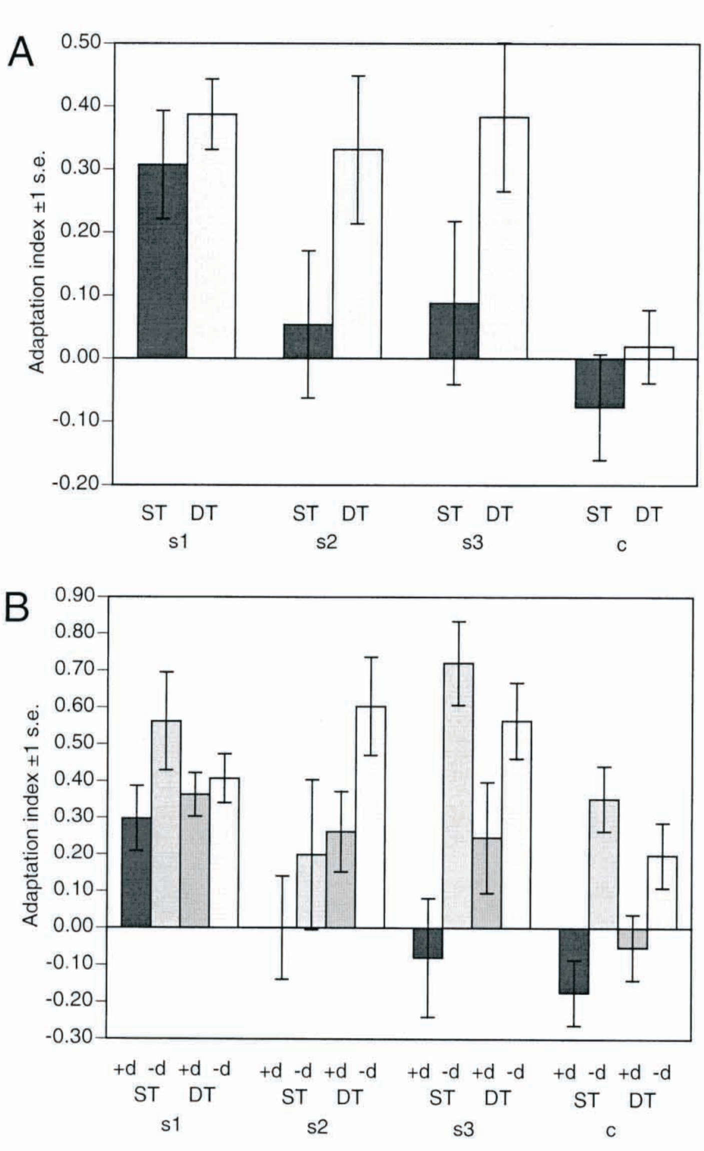

Figure 5. (A) Average adaptation indices with standard errors in the nonadaptive single-task (ST) and dual-task (DT) conditions. (B) The same data, analysed contingent on positive (+d) and negative (–d) detection responses.

attention, because it concerns the attentional requirements of *suppressing* phase correction, which is at least in part a cognitive strategy.

Some striking individual differences must be mentioned here. One participant showed large positive adaptation indices during synchronization but small A(c) indices, which suggests a specific inability to suppress phase correction. Two other participants had strongly negative A(s2) and A(s3) indices in the single-task condition; for one of them, but not for the other, the A(c) index was also strongly negative. This suggests an intentional counteradaptive strategy that, in one case at least, was mediated by period correction. The strategy did not emerge immediately (s1), and it was much less pronounced in the dual-task condition, which indicates that it required attention. Other participants may have applied weaker counteradaptive strategies that were just sufficient to cancel the effect of automatic phase correction and that perhaps were relinquished during continuation tapping.

The results of the detection-contingent analyses of the data from the nonadaptive conditions are shown in Figure 5B.[5] The ANOVA on the synchronization vs. continuation contrast yielded a reliable effect of awareness, $F(1, 9) = 70.3$, $p < .001$: Adaptation indices were generally larger when the tempo changes were not detected, which indicates that suppression or counteradaptive strategies were less effective in the absence of awareness. Such automatic recovery had been expected for phase correction, but the A(c) indices for –d trials also were significantly positive, especially in the single-task condition, which again indicates that period correction, too, has an automatic component. The main effect of attention was nonsignificant in this analysis, but the Awareness × Attention interaction reached significance, $F(1, 9) = 7.2$, $p < .03$, because the overall effect of awareness was larger in the single-task than in the dual-task condition, even though this was not true in position s2.

The main effect of awareness was also significant in the ANOVAs on the other two contrasts, $F(1, 9) = 45.4$, $p < .001$, and $F(1, 9) = 27.1$, $p < .002$, respectively. The Awareness × Attention interaction was significant in the s1 vs. s2 and s3 contrast, $F(1, 9) = 8.2$, $p < .02$, but not in the s2 vs. s3 contrast, $F(1, 9) = 4.5$, $p < .07$.

Estimation of phase and period correction parameters

So far, we have regarded the results in terms of their qualitative consistency with the two-process model of error correction, a consistency that seemed quite encouraging. We now report parameter estimates based on the two-process model, which enabled us to separate the contributions of phase and period correction to adaptation during synchronization, where the two processes operate simultaneously. A brief statement of the model is provided in the Appendix. We implemented the equations in Excel and MATLAB and fitted the model to the adaptation indices by determining the α (phase correction) and β (period correction) parameters that yielded the smallest root-mean-square deviation (rmsd) of the predicted from the obtained indices. This was done for each individual participant in each condition. In analogy to the analyses reported in Figures 4 and 5, we estimated the α and β parameters first without taking the detection responses into account, and we subsequently estimated them contingent on the detection responses, which naturally yielded less reliable estimates, especially for –d trials.

In fitting the model to the data from the adaptive conditions, the individual model fits ranged from excellent (rmsd = 0.008) to very poor (rmsd = 0.232). Nevertheless, we obtained seemingly reasonable parameter estimates for all participants in the adaptive condition. The average values of α and β for the single-task and dual-task conditions are shown in Figure 6A.

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[5] One participant did not have enough data points for calculating reasonable slopes of regression lines for –d trials in the dual-task condition. The participant's noncontingent dual-task adaptation indices were used instead.

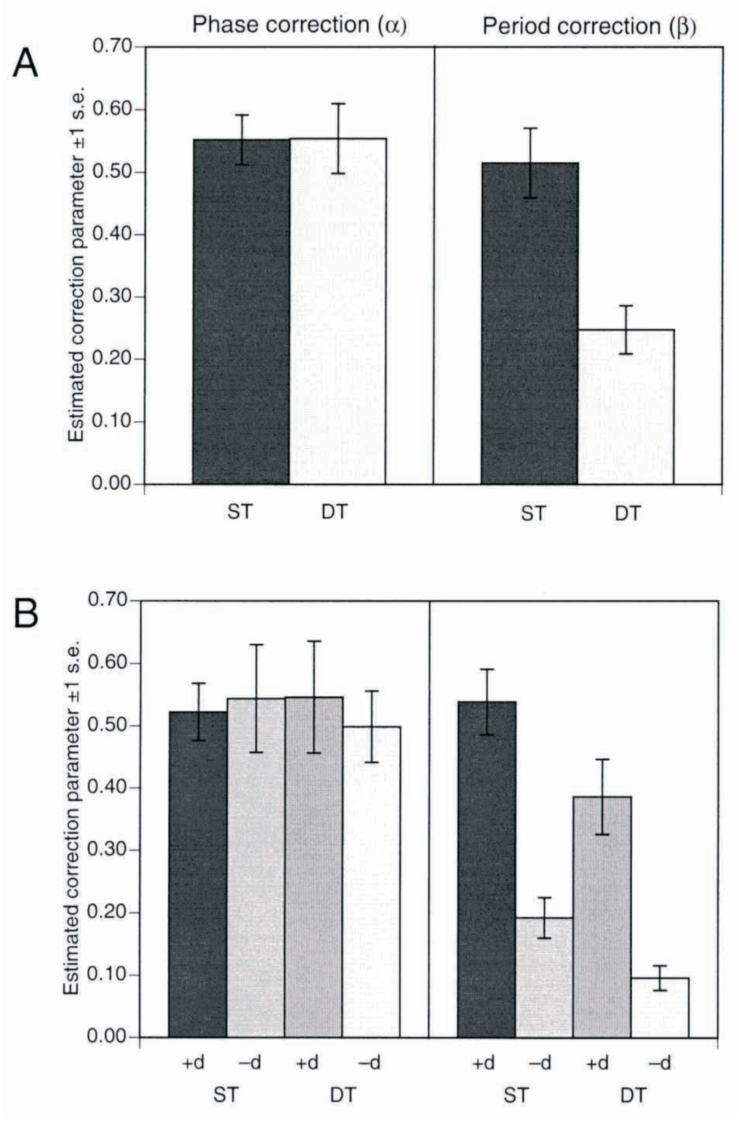

Figure 6. (A) Average estimates of phase correction (α) and period correction (β) parameters with standard errors in the adaptive single-task (ST) and dual-task (DT) conditions. (B) Parameter estimates for a subset of the data ($n = 8$) contingent on positive (+d) and negative (–d) detection responses.

It is clear that α was not affected by the attentional manipulation, whereas β was much lower in the dual-task than in the single-task condition, $F(1, 9) = 48.8$, $p < .001$. These results offer strong support for our hypothesis that only period correction would be affected by attention.

When fitting the model to the individual detection-contingent data, again a number of very poor fits were obtained, but only two participants' data yielded truly unreasonable parameter estimates in the single-task (–d) condition. We excluded these data because they would have distorted the averages. The average parameter estimates of the remaining eight participants are shown in Figure 6B. There were no significant effects of either attention or awareness on α values. For β values, however, both main effects were significant, $F(1, 7) = 17.2, p < .005$, and $F(1, 7) = 28.1, p < .002$, whereas the interaction was not significant. Thus, these results confirm our prediction that only period correction would be affected by attention and awareness, and they reinforce the conclusion that the two effects are independent of each other.

Although fitting a two-parameter model to the data yielded meaningful results in the case of the adaptive conditions, this was not the case with the nonadaptive conditions. The model definitely cannot account for the large decrease in the adaptation indices after the initial PCR in the single-task condition (Figure 5A). Therefore, at least one additional parameter is needed to accommodate the data. We therefore fitted a three-parameter model with parameters α_1 (for s1), α_2 (for s2 and s3), and β. In introducing two phase correction parameters rather than two period correction parameters, we were assuming that it was the suppression of phase correction that became more effective after the initial PCR. (An alternative but less parsimonious assumption would be that the reduced adaptation in positions s2 and s3 reflects a counteradaptive period correction strategy that was abandoned during continuation tapping.)

Figure 7A shows the average parameter estimates derived from fitting this model to the individual data. These results suggest that neither the initial phase correction (i.e., the PCR) nor period correction were significantly affected by the attention manipulation. Participants' ability to suppress phase correction evidently increased from s1 to s2 and s3, but less so when attention was diverted to the arithmetic task. The effect of attention on α_2 was significant, $F(1, 9) = 15.4, p < .004$.

In fitting the model to the detection-contingent individual data, three participants showed extremely poor model fits in the single-task (–d) condition, but their parameter values were not unreasonable. Another participant, however, showed both a poor model fit and parameter values far outside the range of the other participants' values in the dual-task (–d) condition; his data were excluded. The results for the remaining nine participants are shown in Figure 7B. The α_1 values show large variability, especially in the single-task condition, and there were no significant effects in the ANOVA. Thus the results do not contradict the conclusion that the involuntary PCR was unaffected by both attention and awareness. For the α_2 values, the main effect of attention obtained in the noncontingent analysis (Figure 7A) was no longer significant, $F(1, 8) = 2.0, p < .20$. Instead, the main effect of awareness reached significance, $F(1, 8) = 7.1, p < .03$. The interaction was far from significance. This suggests that, in the absence of awareness of a tempo change, participants were less successful in suppressing phase correction in positions s2 and s3. However, the result must be viewed with caution in view of the weak and inconsistent effects. By contrast, the results for β were very reliable: There was no effect of attention but a significant effect of awareness, $F(1, 8) = 66.9, p < .001$. The positive β values for –d trials confirm that there is a small automatic component of period correction that emerges in the absence of awareness of a tempo change. When participants are aware of a tempo change (+d trials), however, that component can be suppressed completely, and the suppression does not seem to require attentional resources. Unlike the automatic component of phase correction, the automatic component of period correction is not obligatory.

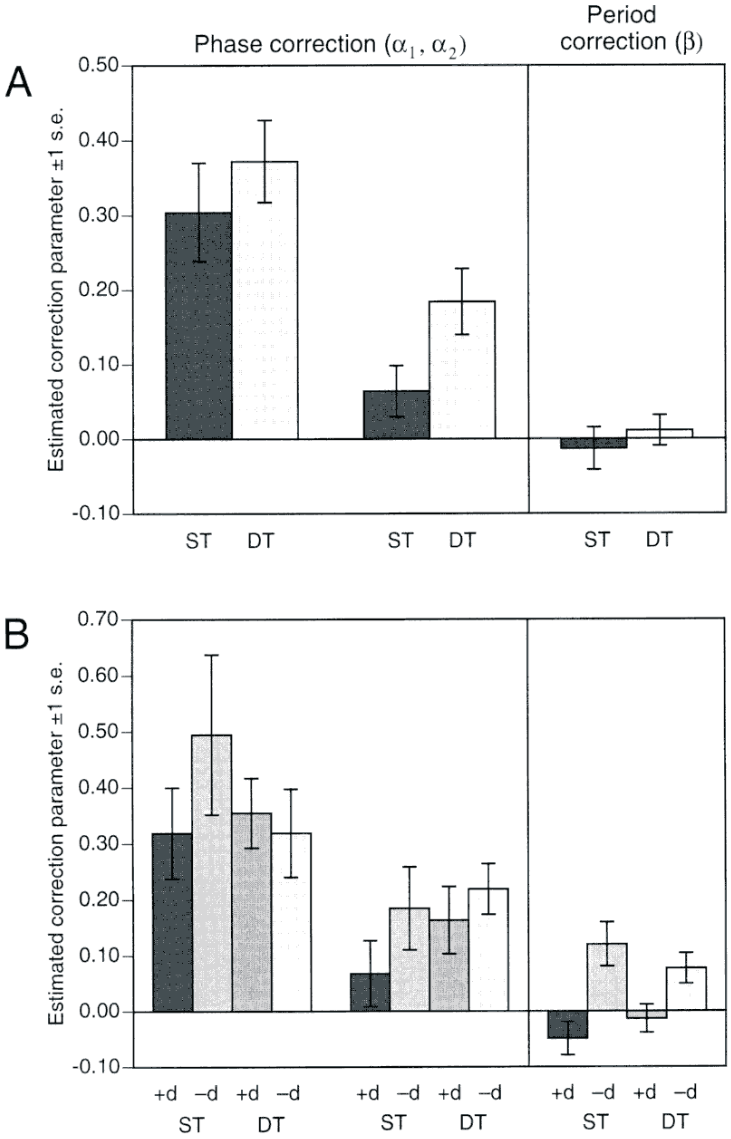

Figure 7. (A) Average estimates of phase correction (α_1, α_2) and period correction (β) parameters with standard errors in the nonadaptive single-task (ST) and dual-task (DT) conditions. (B) Parameter estimates for a subset of the data (n = 9) contingent on positive (+d) and negative (–d) detection responses.

Discussion

In this study, we have explored further the two-process model of error correction in synchronization, which was originally proposed by Mates (1994a, 1994b) and later embraced by Repp (2001a, 2001b). As already noted, the model is conceptually similar to the well-known two-level timing model of Wing and Kristofferson (1973) for free (continuation) tapping. The

Wing–Kristofferson model distinguishes between a central level of timekeeping and a peripheral level of motor implementation, a distinction that is of course also valid in the context of synchronization (see Mates, 1994a, 1994b; Vorberg & Schulze, 2002; Vorberg & Wing, 1996). The Mates model distinguishes between two processes of error correction or adaptation that occur only in synchronization. One of these processes (period correction) clearly applies to the central timekeeper, whereas the other (phase correction) can be thought of as being more closely related to motor implementation in the brain. These processes are examples of action planning and on-line control, a distinction discussed extensively in the context of visuo-spatial tasks (e.g., Glover & Dixon, 2001, 2002; Jeannerod, 1988; Rossetti & Pisella, 2002; Woodworth, 1899).

In accord with this conception, the main hypothesis pursued in the present research was that period correction is less automatic and more subject to cognitive control than is phase correction. Several additional reasons could be cited for entertaining this hypothesis. For example, coupled limit-cycle oscillators representing physical systems will entrain their observable phase and period to each other, or unilaterally, within certain limits (Pikovsky et al., 2001). This dynamic process is analogous to phase correction. The limits of phase (and period) entrainment are set by the difference ("detuning") between the oscillator's *intrinsic* (natural) periods, which are a fixed function of physical properties such as mass and stiffness. Physical oscillators do not have control over their intrinsic period; that is, they are not capable of period correction. Synchronization over a wide range of frequencies requires an executive process (effectively, an internal driving force with a flexible period) that can transcend the biophysical properties of the driven oscillator, such as a tapping finger, which would otherwise limit synchronization performance. Such an executive process is properly called cognitive. Another motivation for our hypothesis, already alluded to in connection with Figure 1 and the Appendix, is that period correction is based on a more complex form of sensory evidence—namely, on a difference between intervals ("relative period")—than is phase correction, which is triggered by a difference between time points (or relative phase). An interval comparison (a second-order difference) is likely to require more cognitive resources than the registration of a simple phase discrepancy (a first-order difference), which even inanimate dynamic systems can perform.

The results offered strong support for our hypothesis. The three main results concern the effects of intention, attention, and awareness—variables that are all more likely to impinge on cognitive processes than on on-line action control. First, we showed that period correction can be suppressed entirely when the intention is not to adapt to a tempo change, whereas (in agreement with the previous findings of Repp, 2002a, 2002c) phase correction cannot be suppressed completely, at least not in the tap immediately following a phase perturbation (the PCR). Second, we found that a diminution of attentional resources, caused by attention to a concurrent mental arithmetic task, impairs period correction, but not phase correction, when the intention is to adapt to tempo changes. Thus, only period correction seems to require attention, as we had hypothesized. When the intention was not to adapt, suppression of period correction showed no significant effect of attention, whereas suppression of phase correction following the initial PCR seemed to be less effective in the dual-task condition. This result suggests that only the suppression of phase correction requires attention, presumably because of the stronger automaticity of phase correction. Alternatively, if this apparent suppression of phase correction really was due to counteradaptive period adjustments, its sensitivity to attentional demands is likewise consistent with our main hypothesis. Third, we replicated previous findings (Repp, 2000, 2001b) that period correction following a tempo change depends on awareness of the tempo change, whereas phase correction does not, given the intention to adapt. When the intention was not to adapt, period correction showed a significant recovery in the absence of awareness, which revealed an automatic (but apparently not obligatory) component of period correction. Although these effects are consistent with a causal role of awareness, it is also possible that the association of awareness with more effective period correction is mediated by a third factor that affects both, such as fluctuations in attention over time and across trials.[6] In that case, the effects of awareness and attention represent independent sources of attentional variation (endogenous and exogeneous, respectively), which explains the lack of an interaction.

In addition, our results demonstrated an expected effect of attention on the detection of tempo changes and furthermore showed that the effect of reduced attention on period correction was not mediated by a reduced awareness of tempo changes. Diversion of attentional resources diminished period correction even in the absence of awareness, which suggests that the resources involved were consumed by the process of period correction itself, not by conscious control of that process. Sergent, Hellige, and Cherry (1993) examined the effect of a secondary cognitive task (anagram solving) on free finger tapping and showed, after decomposing the variance according to the Wing–Kristofferson model into timekeeper and motor implementation components, that only the timekeeper variance was affected. This finding is consistent with ours in that it suggests that the effective maintenance of a constant period (which may be conceptualized as continuous updating from some long-term interval memory) requires attention, as does a deliberate change of the period.

Although our results were statistically reliable and seemed theoretically meaningful, we also found that the two-process model of error correction did not fit the data as well as we would have liked. In particular, the model could not account for the adaptation indices obtained in the second and third positions (s2 and s3) following a tempo change. In the adaptive conditions, these indices were larger than predicted, whereas in the nonadaptive conditions, they were smaller than predicted, especially in the single-task condition. Clearly, the extent to which phase correction and period correction can be controlled strategically requires further investigation.

We certainly expect the distinction between phase correction and period correction to be reflected in different patterns of brain activity. A recent PET study by Stephan, Thaut, Wunderlich, Schicks, Tian, Tellmann et al. (2002) is highly pertinent in that regard, although the authors' theoretical perspective and terminology are different from ours. In that study, participants synchronized finger taps with auditory sequences having several degrees of predictable temporal modulation. Small degrees of IOI modulation, which were below the detection threshold, elicited tracking behaviour (i.e., lag 1 cross-correlated modulation of the ITIs), whereas larger modulations, of which participants were aware, elicited anticipatory behaviour (i.e., lag 0 cross-correlated modulation of the ITIs; see Repp, 2002d). Stephan et al. found that the two types of behaviour were associated with activation of different areas in prefrontal cortex (ventral and dorsolateral, respectively), which are known to be involved in

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[6] We are grateful to an anonymous reviewer for drawing our attention to this important point.

the automatic and voluntary control of action, respectively. (On the latter, see the review by Jahanshahi & Frith, 1998.) Differential parietal, thalamic, and cerebellar activity was observed as well. In our view, tracking is a consequence of phase correction, whereas anticipation reflects an intentional modulation of the timekeeper period (Repp, 2002d). Therefore, Stephan et al. (2002) may well have succeeded in pinpointing the neural substrates of phase and period correction.[7] Prefrontal cortex is also involved in mental calculation, as shown in a fMRI study by Rueckert, Lange, Partiot, Appollonio, Litvan, Le Bihan et al. (1996). Thus, it is one likely site where mental arithmetic may inhibit period correction, perhaps because of common memory or attentional demands. To confirm these speculations, our experiment would have to be taken into the scanner.

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[7] As this article went to press, a new ERP study has come to our attention which provides strong support for the two-process theory of error correction (Praamstra, Turgeon, Hesse, Wing, & Perryer, in press).

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APPENDIX
The two-process error correction model

The model is based on Mates (1994a, 1994b) and Repp (2001a, 2001b). All expressions are stated in terms of expected values and neglect sources of random noise or processing delays. This version of the model is appropriate for fitting data that have been averaged over a number of trials. For simplicity, the expectation operator (E) is omitted in the equations.

Consider period correction first. Let us assume that, when a step change Δ occurs in IOI_{n-1}, the internal timekeeper period is $\mathrm{T}_{n-1} = \mathrm{IOI}_{n-2} = \mathrm{C}$. The discrepancy between $\mathrm{IOI}_{n-1} = \mathrm{C} + \Delta$ and $\mathrm{T}_{n-1} = \mathrm{C}$ causes period correction, so that the next timekeeper period, T_n, includes a proportion β of the discrepancy:

$$\begin{aligned}\mathrm{T}_n &= \mathrm{T}_{n-1} + \beta(\mathrm{IOI}_{n-1} - \mathrm{T}_{n-1})\\ &= \mathrm{C} + \beta\Delta\end{aligned}\tag{1}$$

The next two timekeeper periods during synchronization then will be

$$\begin{aligned}\mathrm{T}_{n+1} &= \mathrm{T}_n + \beta(\mathrm{IOI}_n - \mathrm{T}_n)\\ &= \mathrm{C} + \beta\Delta + \beta((\mathrm{C} + \Delta) - (\mathrm{C} + \beta\Delta))\\ &= \mathrm{C} + \beta\Delta(1 + (1 - \beta))\end{aligned}$$

$$\begin{aligned}\mathrm{T}_{n+2} &= \mathrm{T}_{n+1} + \beta(\mathrm{IOI}_{n+1} - \mathrm{T}_{n+1})\\ &= \mathrm{C} + \beta\Delta(1 + (1 - \beta)) + \beta((\mathrm{C} + \Delta) - (\mathrm{C} + \beta\Delta(1 + (1 - \beta)))\\ &= \mathrm{C} + \beta\Delta(1 + (1 - \beta) + (1 - \beta)^2)\end{aligned}$$

or more generally,

$$\mathrm{T}_{n+k} = \mathrm{C} + \beta\Delta\Sigma_i(1 - \beta)^i \text{ for } \mathrm{i} = 0, \ldots, k\tag{2}$$

This expression converges exponentially onto $\mathrm{C} + \Delta$. The A(c) index in our experiment is the slope of this linear relation and hence an estimate of $\beta\Sigma_i(1 - \beta)^i$ for $k = 2$.

Now consider phase correction, which is informed by asynchronies. The expected relative asynchrony (i.e., deviation from the mean asynchrony) preceding the first phase-shifted tone in the sequence, a_{n-1}, is zero, so that the expected asynchrony between the tap and the first phase-shifted tone in the sequence is $\mathrm{a}_n = -\Delta$. On the basis of this perceptually registered asynchrony, phase correction adjusts the time of occurrence of the next tap by a proportion α of a_n, so that the next asynchrony becomes (cf. Repp, 2001a):

$$\begin{aligned}\mathrm{a}_{n+1} &= \mathrm{a}_n + \mathrm{T}_n - \mathrm{IOI}_n - \alpha\mathrm{a}_n\\ &= -\Delta + (\mathrm{C} + \beta\Delta) - (\mathrm{C} + \Delta) + \alpha\Delta\\ &= -\Delta(2 - (\alpha + \beta))\end{aligned}\tag{3}$$

The intertap interval ITI_n is defined as

$$\begin{aligned}\mathrm{ITI}_n &= \mathrm{IOI}_n - \mathrm{a}_n + \mathrm{a}_{n+1}\\ &= (\mathrm{C} + \Delta) + \Delta - (2 - (\alpha + \beta))\\ &= \mathrm{C} + \Delta(\alpha + \beta)\end{aligned}\tag{4}$$

This corresponds to position s1 in our paradigm, and it is evident that the A(s1) index, the slope of the linear regression, is an estimate of $(\alpha + \beta)$.

The more complex formulas for the ITIs in positions s2 and s3 can be derived by applying Equations 3 and 4 recursively.