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Phase Attraction in Sensorimotor Synchronization With Auditory Sequences: Effects of Single and Periodic Distractors on Synchronization Accuracy

Bruno H. Repp
Haskins Laboratories

Four experiments showed that both single and periodic distractor tones affected the timing of finger taps produced in synchrony with an isochronous auditory target sequence. Single distractors had only small effects, but periodic distractors occurring at various fixed or changing phase relationships exerted strong phase attraction. The attraction was asymmetric, being stronger when distractors preceded target tones than when they lagged behind. A large pitch difference between target and distractor tones (20 vs. 3 semitones) did not reduce phase attraction substantially, although in the case of continuously changing phase relationships it did prevent complete capture of the taps by the distractors. The results support the hypothesis that phase attraction is an automatic process that is sensitive primarily to event onsets.

Sensorimotor synchronization, such as finger tapping in phase with an isochronous auditory sequence, is made possible by continuous error correction based on sensory feedback. Without such error correction, the taps would soon drift away from the sequence events because of cumulative error (Hary & Moore, 1987; Vorberg & Wing, 1996). The internal process that helps maintain synchrony despite endogenous variability in motor timing is called *phase correction.* A simple linear model, according to which the timing of each tap is adjusted by a constant proportion of the asynchrony between the preceding tap and the preceding sequence event, accounts well for the statistical properties of asynchronies and intertap intervals (Mates, 1994a, 1994b; Pressing, 1998, 1999; Semjen, Schulze, & Vorberg, 2000; Vorberg & Schulze, 2002; Vorberg & Wing, 1996). The model can also explain adjustments in tap timing that follow small experimenter-introduced perturbations in a sequence. For example, when the sequence events are phase-shifted slightly from a certain point on, the taps quickly adapt to the new phase, even when the shift is below the perceptual detection threshold (Repp, 2000, 2001a). Because participants in such experiments have the intention (as well as a natural tendency) to move in synchrony (i.e., in phase) with an auditory sequence, the sequence events may be said to attract the finger taps. Phase correction is the internal process that mediates this observable *phase attraction.*

The observable asynchrony between taps and sequence events (tones, say) usually deviates from zero, even when averaged over many cycles and trials. Typically, taps precede tones by some tens of milliseconds. Several explanations of this anticipation tendency have been proposed, but they do not concern us here (see, e.g., Aschersleben & Prinz, 1995; Prinz, 1997; Wohlschläger & Koch, 2000). The average asynchrony presumably corresponds to an internal asynchrony of zero or, in other words, to a point of subjective simultaneity. Therefore, it is often convenient to analyze synchronization data in terms of *relative asynchronies* (deviations from the mean or from some other reference asynchrony) or *relative shifts* (deviations of taps from their expected times of occurrence).

A recent series of experiments (Repp, 2002a) has demonstrated that phase attraction is difficult to resist. In these experiments, participants tapped in synchrony with auditory sequences containing a single phase-shifted tone (referred to as an *event onset shift* or EOS) and tried hard not to react to it, knowing that this strategy would reduce asynchronies with subsequent tones that were not phase-shifted. Nevertheless, the tap following the EOS involuntarily shifted in the same direction as the tone. The relative shift of the tap (i.e., relative to when it would have been expected to occur in the absence of an EOS) was termed the *phase correction response* (PCR). The PCR was substantially smaller when participants intended not to react than when they intended to adapt to phase perturbations in the sequence; at least, this was true when the perturbation was above the detection threshold (Repp, 2002c). Thus, phase correction is subject to voluntary control, but it cannot be suppressed completely.

Several synchronization experiments have indicated that phase correction, whether intended or not, is insensitive to pitch differences that affect auditory grouping, stream segregation, and perception of timing. In one experiment (Repp, 2000, Experiment 5), a pitch change occurred in the middle of a sequence containing also a small phase shift. A positive shift (phase delay) was more difficult to detect when it coincided with the pitch change, presumably due to grouping of tones with the same pitch (Thorpe & Trehub, 1989; Thorpe, Trehub, Morrongiello, & Bull, 1988), but phase correction in synchronized finger tapping was unaffected. In another experiment, which examined the PCR to an EOS (Repp, 2002a, Experiment 1), the shifted tone either had the same pitch as the other sequence tones or was lower by almost four octaves, which made it stand out perceptually. Nevertheless, the PCR was unaffected by the pitch difference.

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Correspondence concerning this article should be addressed to Bruno H. Repp, Haskins Laboratories, 270 Crown Street, New Haven, Connecticut 06511-6695. E-mail: repp@haskins.yale.edu

In Experiment 2 of the same study (Repp, 2002a), the PCR to an EOS was found to be equally large in in-phase and antiphase tapping. In that study's Experiments 3 and 4, participants tapped in synchrony with one of two interleaved tone sequences of different pitch that alternated in strict antiphase. Let us call them the *target* and *distractor* sequences, respectively. An EOS occurred either in the target sequence or in the distractor sequence. In each case, an average PCR was obtained that was about half as large as the average PCR obtained in tapping (in phase or in antiphase) to a single sequence containing an EOS. Thus, the presence of an unperturbed sequence had a stabilizing influence, and the PCR may be seen as a combined response to the EOS in one sequence and the absence of an EOS in the other sequence. Exactly the same results were obtained when the pitch difference between the target and distractor sequences was increased from 3 to 20 semitones (st). The greater pitch difference presumably facilitated auditory segregation and selective attention to the target sequence, but it left the PCR unaffected. These findings led to the hypothesis that phase correction is sensitive only to the timing of event onsets but not to other auditory properties that influence perceptual organization and judgment. In other words, phase correction—more precisely, the automatic component of phase correction—was hypothesized to be an action control process dedicated to the registration of purely temporal information.

This hypothesis was pursued further in the present research by means of new distractor paradigms in which the pitch difference between targets and distracters was varied. Each experiment also included a range of temporal relationships, or relative phases, between targets and distractors. Experiment 1 presented single distractors, whereas Experiments 2–4 used periodic distractor sequences.

Specifically, Experiment 1 investigated whether a PCR could be elicited by a single distractor tone occurring somewhere inbetween the tones of an isochronous target sequence. It was predicted that the distractor tone would exert phase attraction and thus elicit an automatic PCR. However, because an unperturbed target tone would be present as well, the PCR should be smaller than that obtained when, instead of inserting a distractor tone, a target tone was shifted to the distractor location (i.e., an EOS). Moreover, given the earlier finding that phase correction is insensitive to pitch differences between target and distractor tones, not only should the pitch of the distractor tone be irrelevant but interchanging the pitches of a target tone and a distractor tone should also lead to a PCR of the same magnitude. Confirmation of these predictions would provide further support for the hypothesis that the phase correction process is sensitive merely to tone onsets, regardless of pitch.

Experiments 2–4 used isochronous sequences of distractor tones that differed in pitch from the tones of an isochronous target sequence. In Experiment 2, the target and distractor sequences had the same tempo but varied in their temporal relationship (relative phase) from trial to trial. Thus, Experiment 2 investigated the *cumulative phase attraction* exerted by distractor tones occurring repeatedly at a fixed phase relationship. This phase attraction was expected to be reflected in the asynchronies between taps and target sequence tones. In Experiments 3 and 4, the target and distractor sequences had different tempi, so that their phase relationship changed continuously. This paradigm tested participants' ability to maintain synchrony with the target sequence in the presence of systematically waxing and waning (and periodically reversed) phase attraction exerted by the distractor tones. This changing phase attraction was expected to be reflected in periodic modulations of the asynchronies. Experiments 2–4 also varied the pitch distance between target and distractor sequences, a manipulation that, according to the hypothesis that the phase correction process is sensitive only to temporal information, was predicted to have no effect.

The strength of phase attraction was expected to vary nonlinearly with the temporal distance or relative phase between target and distractor tones. In earlier investigations using the EOS paradigm (Repp, 2002a, 2002c; Repp & Penel, 2002), the magnitude of the involuntary PCR was found to increase as EOS magnitude increased to about 20% of the target sequence interonset interval (IOI) and then to reach an asymptote. Accordingly, the PCR to a distractor tone in the presence of a target tone was expected to increase with distractor distance up to about 20% of the target sequence IOI but to be only about half as large as the PCR to an EOS (shifted target tone). At larger temporal separations, the phase attraction of distractor tones was expected to decrease. A distractor tone placed at 50% of the target sequence IOI was not expected to have any effect because positive and negative phase attraction exerted by that tone, if symmetric, would cancel each other. Therefore, the function relating asynchronies or relative shifts to distractor distance was expected to have a roughly sinusoidal shape.

Experiment 1

Experiment 1 explored the effects of single distractor tones on synchronization accuracy. There were eight conditions, which are depicted schematically in Figure 1. The first three conditions were variants of the EOS paradigm and served as controls. They included (Condition 1) a shifted high-pitched tone (H) in a target sequence of high-pitched tones (i.e., an ordinary EOS), (Condition 2) a shifted target tone that in addition had a slightly lower pitch (h) than the other sequence tones, and (Condition 3) a shifted target tone having a substantially lower pitch (L). Rather than shifted target tones, the critical tones in these three conditions may also be regarded as distractor tones occurring close to a missing target tone; indeed, this is the perspective adopted in Figure 1 and henceforth. Conditions 4–7 were the crucial experimental conditions. Conditions 4 and 5 were like Conditions 2 and 3, respectively, except that a target tone was present; thus, the distractor tone was truly a distractor and could not be mistaken for a shifted target tone.[1] Conditions 6 and 7 were like Conditions 4 and 5, respectively, except that the pitches of target and distractor tones were interchanged. (Again, a distractor is identified by its nontarget location, not by its pitch.) The temporal placement (relative phase) of the distractor tones was varied in Conditions 1–7. Condition 8 consisted merely of an omitted sequence tone. This control condition was included to check for the possibility that the absence of a sequence tone would elicit a PCR, an effect that might be confounded with the effect of a distractor that followed an empty target location in Conditions 1–3. Also, by preparing participants for the occasional presence of a gap in a sequence, inclusion of

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[1] A condition in which two H tones occurred in close succession, corresponding to Condition 1, was not used because of technical problems in generating such stimuli at very short temporal separations on the available equipment.

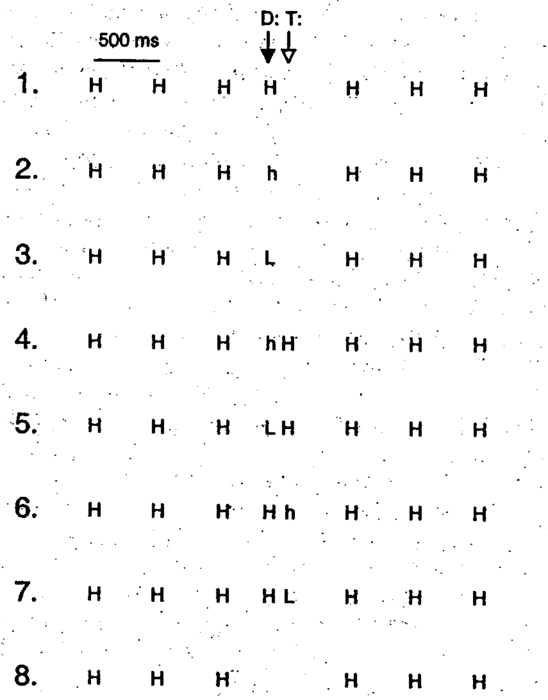

Figure 1. Schematic illustration of the eight conditions in Experiment 1. All distractors precede the target location in these examples. D = distractor; T = target location; H = high-pitched tone; h = slightly lower tone; L = much lower tone.

Condition 8 reduced the probability that a missing target tone would be mistaken for the end of the sequence.[2]

Conditions 1–7 were all expected to elicit a PCR (i.e., a shift of the following tap in the direction of the distractor, relative to the nearest target position). According to the hypothesis that phase correction is insensitive to pitch differences, Conditions 1–3 were all expected to yield the same outcomes, as were Conditions 4–7. However, the PCRs in Conditions 4–7 were expected to be only about half as large as those in Conditions 1–3 because the phase correction process would be engaged by both the distractor and an unperturbed target tone.

Method

Participants. The 8 participants (6 women, 2 men) were all moderately practiced in synchronized tapping, having participated in a number of previous experiments of a similar nature. In particular, they were familiar with the task of trying not to react to EOSs. They included 4 undergraduate students and 2 graduate students who were paid for their participation, as well as a postdoctoral researcher and myself.[3] Ages ranged from 19 to 27, except for me; I was 55 at the time. Musical training ranged from little (a few years) to considerable (10 years or more).

Materials. The target sequences consisted of between 15 and 19 high-pitched tones (not counting any added or deleted tones). The distractor tone or missing tone occurred in or near Sequence Position 9, 10, 11, 12, or 13, and there were always 6 target tones following this critical position. The high (H) pitch was 4192 Hz (C_8), the slightly lower pitch (h) was one semitone lower (3952 Hz, B_7), and the low (L) pitch was eight semitones lower (2640 Hz, E_7). The target sequence had IOIs of 500 ms. The distractor tone occurred in one of 10 possible temporal relations to the nearest target location: −160, −80, −40, −20, −10, 10, 20, 40, 80, or 160 ms. For convenience, these displacements are referred to as Δ values. In other words, they ranged from ±2% to ±32% of the IOI, or from ±0.02 to ±0.32 in terms of normalized relative phase (which ranges from −0.5 to 0.5).

All in all, there were 7 (conditions) × 10 (Δ values) × 5 (sequence positions) = 350 different sequences in Conditions 1–7, to which were added 5 (sequence positions) × 5 (replications) = 25 sequences for Condition 8. These 375 sequences were arranged into five blocks of 75 sequences each. In each block, each Δ value in Conditions 1–7 occurred once, and each of the 5 sequence positions in Condition 8 occurred once. Another set of five blocks was assembled in the same way. The sequence position of distractors or gaps was varied only to prevent temporal expectations and was not considered further in the data analysis. Thus, in the course of the 10 blocks, each Δ value in Conditions 1–7 occurred 10 times, and sequences containing a gap (Condition 8) occurred 50 times. The order of sequences within blocks was random. Each block was divided into two halves to allow for a break.

The sequences were produced on a Roland (Los Angeles, CA) RD-250s digital piano via a musical instrument digital interface (MIDI) translator under control of a MAX patch running on a Macintosh Quadra 660AV computer (Apple, Cupertino, CA).[4] The tones (sounding rather like pings) had sharp onsets and decayed rapidly within about 100 ms; no "note offset" was specified in the MIDI instructions. All tones were produced at the same nominal intensity (MIDI key velocity). The lower tones sounded somewhat louder than the higher tones, but no attempt was made to equate loudness levels.

Procedure. The experiment lasted about 3 hours and was divided into three sessions on different days. Sequence presentation and recording of finger taps were controlled by the MAX patch. Participants sat in front of a computer monitor on which the current trial number was displayed, listened to the sequences over Sennheiser (Old Lyme, CT) HD540 II earphones, and tapped on a Fatar Studio 37 MIDI controller (a silent three-octave piano keyboard; Music Industries Corporation, Garden City, NY) by depressing a white key with the index finger of the preferred hand in synchrony with the target sequence tones. The MIDI controller was held on the lap, and participants were asked to keep their finger in contact with the response key, which moved vertically by about 1 cm. The key had a cushioned bottom contact and did not produce any audible impact sound unless it was struck rather hard (as may have been the case with some 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 and to avoid reacting to any distractor tones or missing tones. They understood that this strategy would result in synchrony with the following sequence tones.

Results

As is commonly observed in synchronization tasks, the taps generally preceded the sequence tones. The grand average asyn-

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[2] I am grateful to Mimi Kim for first bringing this problem to my attention.

[3] I routinely run myself first in each experiment and include my data, which usually are in agreement with those of other participants.

[4] A MAX patch is a program written in the graphical programming language MAX. Because of a peculiarity of this software, the tempo of the output was about 2.4% faster than specified in the MIDI instructions, as determined in earlier acoustic waveform measurements. Thus, the target sequence IOI was actually 488 ms, not 500 ms. The participants' key presses were registered at a correspondingly slower rate. Throughout this article, all millisecond values are reported as they appeared in the MAX environment. Apart from the constant scaling factor, MAX is believed to be highly accurate (within 1 ms) in timing the sequences and registering the key presses. Note that normalized relative phase values were unaffected by the scaling.

chrony, computed across all sequences and participants from the three taps preceding the critical position, was −65 ms, with individual averages ranging from −28 ms to −122 ms.[5] (Three participants showed unusually large anticipation effects.) The data were analyzed in terms of the relative shift (in milliseconds) of the tap following the critical position. This was the PCR, and it was computed by subtracting the shift of the tap in the critical position from the shift of the following tap.[6] The shift of each tap was defined as its deviation from the nearest theoretical target position, regardless of whether a target tone was present (in which case the shift was the asynchrony) or absent. For example, if the tap in the critical position was shifted by −50 ms and the following tap was shifted by −74 ms (both shifts reflecting the general anticipation tendency), the PCR would be −24 ms.

The results of Conditions 1–3 are shown in the three panels of Figure 2. These are the conditions in which a distractor tone occurred without a target tone. The average PCRs are shown with double standard error bars (~95% confidence intervals) as a function of Δ, which is represented on a quasi-logarithmic scale. It is apparent that the PCRs were small but reliably different from zero in most cases. PCR magnitude increased up to Δ values of ±80 ms, as predicted, and perhaps a bit further for negative Δ values. Between-participants variability also increased with $|\Delta|$. The average magnitude of the PCRs is consistent with that observed for EOSs in earlier experiments (Repp, 2002a, 2002c). The results of the three conditions were similar, which is consistent with the hypothesis that pitch differences are irrelevant to phase correction.

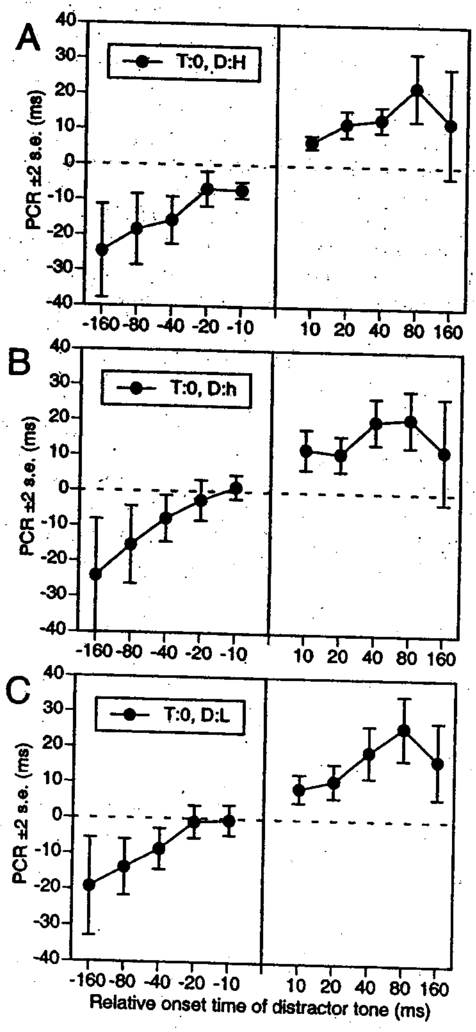

Figure 2. Results of Conditions 1–3 in Experiment 1. The average phase correction response (PCR) is shown as a function of the relative onset time of the distractor tone (Δ value), with double standard error bars. T = target; 0 = absent; D = distractor; H = high pitch; h = slightly lower pitch; L = low pitch.

A repeated measures analysis of variance (ANOVA) with the variables of condition (3), direction (negative vs. positive Δ), and absolute magnitude of Δ (5) was conducted after changing the sign and reversing the order of the data for negative EOSs (effectively, rotating them by 180° around the origin). The Greenhouse–Geisser correction was applied to p values where appropriate, and the value of ε is reported. The main effect of $|\Delta|$ was significant, $F(4, 28) = 5.3$, $p < .04$, $\varepsilon = .32$, because of the change in PCR magnitude with $|\Delta|$. The main effect of condition, which would have indicated an effect of distractor pitch, did not reach significance, $F(2, 14) = 3.3$, $p < .08$, $\varepsilon = .96$. However, there was a significant Condition × Direction interaction, $F(2, 14) = 12.5$, $p < .006$, $\varepsilon = .64$: The average magnitude of PCRs to negative EOSs decreased from Condition 1 to Condition 3, whereas that of PCRs to positive EOSs increased slightly. Although this result suggests that distractor pitch played some role, it is difficult to interpret and could reflect a difference across conditions in the extent of phase drift.

The results of Conditions 4–7 are shown in Figure 3. As predicted, the PCRs in these conditions were smaller than in Conditions 1–3. Often, they were not significantly different from zero. In addition, however, their relation to Δ was different. On the negative side, the PCR increased at first with $|\Delta|$ but nearly disappeared at −160 ms. On the positive side, the PCR did not increase at all with Δ. On first glance, the results for the four conditions again seem similar, consistent with the hypothesis that pitch would not make a difference.

Conditions 4–7 were subjected to a repeated measures ANOVA similar to that conducted on Conditions 1–3, except that the condition variable was divided into two crossed variables referring to the lower pitch in the sequence, namely, its location (distractor vs. target) and its height (h vs. L). Overall, the PCRs deviated significantly from zero, $F(1, 7) = 53.9$, $p < .0003$, despite their small size. Unexpectedly, the main effect of location was significant, $F(1, 7) = 11$, $p < .02$: PCRs were larger when the lower tone occurred as a distractor than when it occurred in the target location. A significant main effect of $|\Delta|$, $F(4, 28) = 3.8$, $p < .05$, $\varepsilon = .49$, was due to an overall increase of PCRs with $|\Delta|$ up to 80 ms, but distinctly smaller PCRs at 160 ms. This effect interacted with direction, $F(4, 28) = 3.5$, $p < .05$, $\varepsilon = .64$, because the pattern just

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[5] The fact that the key depressions were registered during the downward movement added up to −20 ms to the asynchronies, depending on the velocity.

[6] Only the immediately preceding tap was taken as the reference to minimize the effect of phase drift, which is common in such short sequences. However, similar results would surely have been obtained if, for example, the average shift of three preceding taps had been taken as the reference.

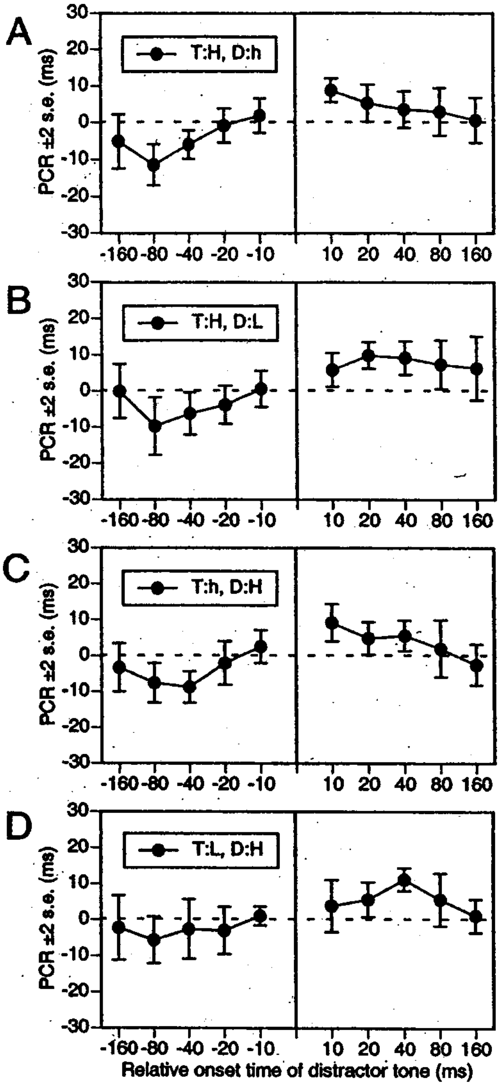

Figure 3. Results of Conditions 4–7 in Experiment 1. The average phase correction response (PCR) is shown as a function of the relative onset time of the distractor tone, with double standard error bars. T = target; H = high pitch; D = distractor; h = slightly lower pitch; L = low pitch.

described derived mainly from negative PCRs. Finally, there was a significant Direction × Magnitude × Height interaction, $F(4, 28) = 5.4$, $p < .008$, $\varepsilon = .70$: When the lower tone was relatively high (h), PCRs to positive Δ values decreased as Δ increased, but when the tone was really low (L), PCRs peaked at an intermediate Δ value (40 ms). These results were a bit more complex than expected, but there was no main effect of pitch height.

Figure 4 compares informally the PCRs averaged across Conditions 1–3 with those averaged across Conditions 4–7. The dotted line indicates 50% of the PCRs in Conditions 1–3, which was the predicted size of the PCRs in Conditions 4–7 under the assumption that equal weight would be given to the target and distractor tones, which was expected to be the case at small Δ values. It can be seen that the observed PCRs indeed were generally close to the predictions for small Δ values, but they were smaller than predicted at the largest Δ values (−160, 80, and 160 ms). This indicates that the tone in the target location, regardless of its pitch, exerted a stronger phase attraction than a temporally distant distractor tone. When target and distractor tones were close, however, they seemed to be weighted equally by the phase correction process.[7]

The average PCR in Condition 8 was −2 ms, which was not significantly different from zero. Thus, a gap did not seem to elicit a PCR.[8]

In summary, Experiment 1 demonstrated that single distractor tones do elicit a small PCR but only when they are close to a target tone (within perhaps ±100 ms, or 20% of the IOI) or when there is no target tone, in which case the PCR is larger. Thus, the phase correction process seems to be sensitive to any tone onset occurring in the vicinity of (the perceived temporal location of) a tap. The pitch of the distractor tone (and, incidentally, its associated loudness) seemed to make little difference overall, although it was involved in some interactions. On the whole, the results are reasonably consistent with the hypothesis that the phase correction process is insensitive to pitch differences.

Experiment 2

Whereas Experiment 1 dealt with the effects of single distractor tones, the following experiments examined synchronization with a target sequence that was accompanied by a periodic distractor sequence. In Experiment 2, the target and distractor sequences had the same tempo but differed in pitch. The two experimental variables of interest were the temporal separation (relative phase) and the pitch difference between the tones of the two sequences. The dependent variables were the average asynchrony of the taps and the variability of the asynchronies. It was expected that a distractor sequence occurring either in phase or in antiphase with the target sequence would have no deleterious effect on synchronization performance. In fact, an antiphase distractor sequence might even improve accuracy because it would subdivide the target sequence IOIs evenly (Repp, in press; Semjen, Schulze, & Vorberg, 1992). The question of interest was whether distractor sequences in other phase relationships to the target sequence would affect synchronization accuracy. It was expected that participants' taps would be attracted by close distractor sequences and that this would result in relative shifts and increased variability of the taps. However, the magnitude of the pitch difference between target and distractor sequences was predicted to have little effect.

Method

Participants. Six of the 8 participants (5 women, 3 men) were the same as in Experiment 1. Replacing 2 female undergraduate students, the new participants were a male professional violinist (age 27) and a female volunteer (age 37) who, too, had considerable musical training.

Materials. Each trial consisted of interleaved target and distractor sequences that differed in pitch. All within-sequence IOIs were 500 ms.

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[7] The unequal weighting at larger Δ values seems to contradict the finding of Repp (2002a) that distractor tones occurring in antiphase (±250 ms) were weighted equally with target tones. However, the distractors in that earlier study were continuous sequences, and it was not the distractor sequence as such but an EOS occurring in it that had the equally weighted effect.

[8] One participant reacted very strongly to the gap in 4 out of 50 trials by delaying the next tap by several hundreds of milliseconds, evidently mistaking the gap for the end of the sequence. These trials were excluded.

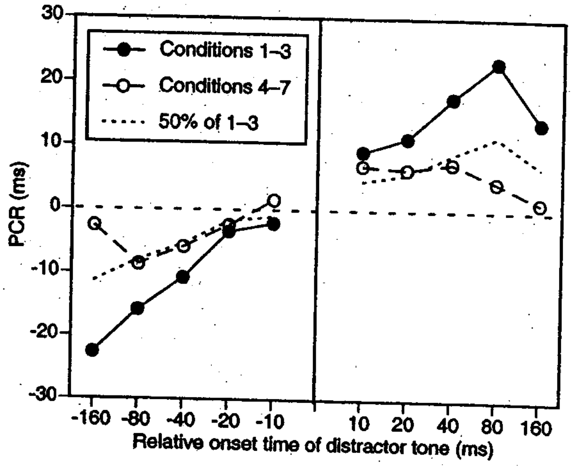

Figure 4. Average phase correction responses (PCRs) in Conditions 1–3 and 4–7 of Experiment 1 as a function of the relative onset time of the distractor tone. The dashed line indicates 50% of the PCRs in Conditions 1–3.

The target sequence contained 21 tones, the distractor sequence 17 tones. The first 4 tones in each trial were always target tones; the distractor sequence started in the vicinity of the 5th target tone. The temporal displacement of the distractor tones relative to the target tones, which is again called Δ, was −160, −80, −40, −20, −10, 0, 10, 20, 40, 80, 160, or 250 ms (equivalent to −250 ms). The corresponding normalized relative phases were 0, ±0.02, ±0.04, ±0.08, ±0.16, ±0.32, and ±0.5. Given a difference in pitch, the target sequence could be either higher or lower in pitch than the distractor sequence. This led to 24 different trials (12 Δ values × 2 pitch assignments), which were presented 10 times in different random orders (blocks) in each of two sessions. In one session, the pitch difference was 3 st (4192 Hz vs. 3520 Hz); in the other session, it was 20 st (4192 Hz vs. 1320 Hz). Because the 1320-Hz tones sounded distinctly louder than the 4192-Hz tones, their nominal intensity was lowered by 10 MIDI keypress velocity units (about 3 dB), which resulted in approximately equal loudness. The equipment was the same as in Experiment 1.

Procedure. Participants came for two sessions, usually one week apart. Four of them did the 3-st condition in the first session, the other 4 did the 20-st condition first. The task was to tap in synchrony with the target sequence (the one that started earlier), beginning with the second tone, and to ignore the distractor sequence.

Results

Average asynchronies with respect to the target sequence were calculated for each participant in each condition by averaging the asynchronies in each trial over Target Sequence Positions 12–21 or Taps 11–20 (i.e., excluding the first 10 taps and the final tap) and across the 10 trials within each condition. The reason the first 10 taps were excluded was that the asynchronies changed gradually following the onset of the distractor sequence, revealing the cumulative effect of the repeated distractor tones. A representative sample of one participant's data, averaged over 10 trials for each Δ value, is shown in Figure 5. The first four taps represent synchronization with the lead-in target tones. (The divergent asynchronies of the first tap most likely represent context effects of the preceding trial.) The distractor sequence started in Position 5 (with the fourth tap), and the asynchronies for the different Δ values can be seen to diverge over the next five taps or so. By the 12th sequence position, a reasonably steady state was generally reached, although considerable drift and variability still occurred.

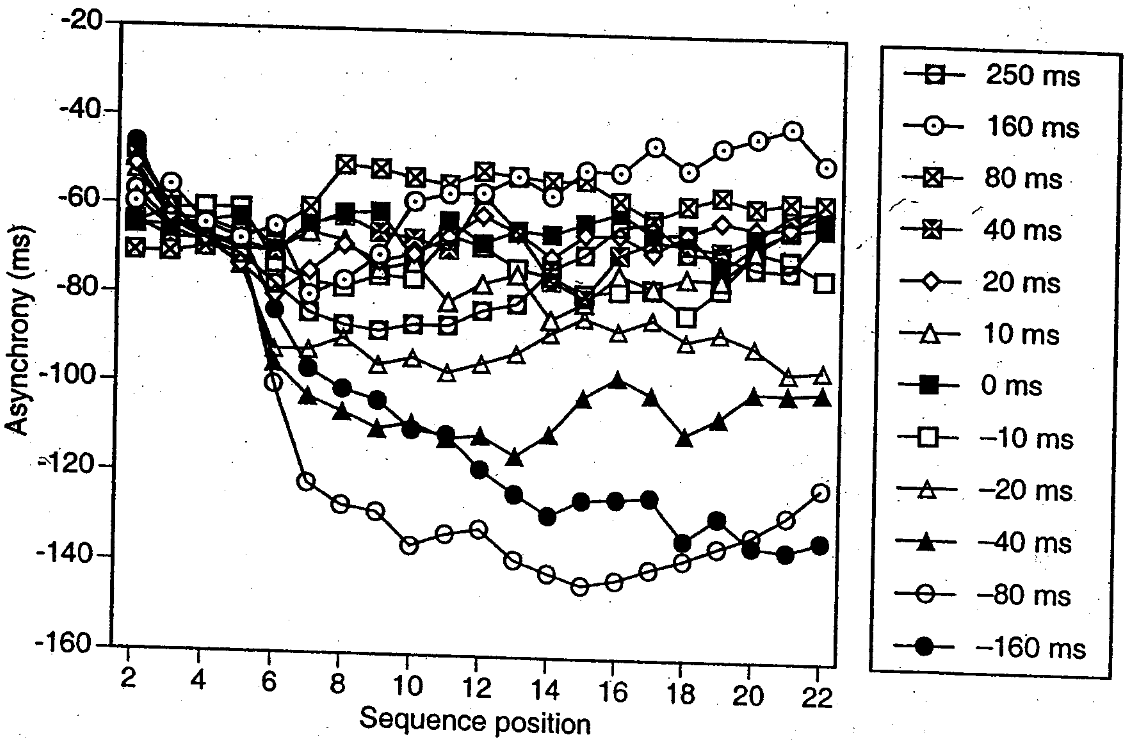

Figure 5. Average asynchronies (across 10 trials) of 1 participant as a function of sequence position for different Δ values (3-semitone pitch separation, high target pitch).

The grand average asynchrony for $\Delta = 0$ was -66 ms, with individual averages ranging from -21 ms to -128 ms. Because these anticipation tendencies were of no special interest here, they were removed by subtracting the average asynchrony for $\Delta = 0$ from those for all Δ values, which resulted in relative asynchronies with $\Delta = 0$ as the reference.

Figure 6A shows the average relative asynchronies as a function of Δ, with standard error bars. The two functions represent the two pitch separations; they (and the standard errors) have been averaged over the two pitch assignments. The left-most and right-most data points (for $\Delta = \pm 250$ ms) are duplicates of each other. It is evident that the distractor sequence had a strong phase attraction effect on the relative asynchronies. The effect was especially pronounced at negative Δ values up to -80 ms. If the distractor sequence had captured the taps completely, the data points would fall on a line with a slope of -1 (dotted line in Figure 6A). This is the case at $\Delta = -10$ ms and -20 ms, where the onsets of the target tones probably were difficult to discern because they were masked by, or fused with, the distractor tones. For the same reason, distractor tones at $\Delta = 10$ ms and 20 ms had no effect. Thus, at these very small separations, participants simply synchronized with the tone that occurred first. However, the data points for $\Delta = -40$ ms and -80 ms still fall fairly close to the dotted line, indicating that participants synchronized their taps more with the distractor sequence than with the target sequence, even though the successive tones were clearly distinguishable at these separations. Even at $\Delta = -160$ ms, there was still a strong phase attraction effect. At $\Delta = \pm 250$ ms, however, the relative asynchrony was not significantly different from zero. When the distractor sequence lagged behind, it also attracted the taps, but the effect was much weaker than at negative Δ values. On the positive side, there also seemed to be an effect of pitch separation, with the distractor effects being smaller at the larger pitch distance. The large effects on the negative side, however, were not affected at all by pitch separation.

A repeated measures ANOVA was conducted on these data, with the variables of pitch separation (3 st or 20 st), target pitch (high or low, discussed later), direction of Δ (negative, positive), and absolute magnitude of Δ (five values). The relative asynchronies for negative Δ values were multiplied by -1 and reversed in order; that is, these data were rotated by 180° around the origin in the x–y plane, so as to be directly comparable to the data for positive Δ values. The data for $\Delta = 0$ and $\Delta = 250$ ms were omitted. The analysis showed significant main effects of direction, $F(1, 7) = 37.9, p < .0005$, and of Δ magnitude, $F(4, 28) = 15.7, p < .004, \varepsilon = .27$. The Direction × Magnitude interaction did not reach significance, $F(4, 28) = 3.1, p < .11, \varepsilon = .32$. All effects involving pitch separation were far from significance. Evidently, the effect of pitch separation at positive Δ values was not consistent across participants.

Two measures of variability were obtained.[9] The standard errors of the average relative asynchronies, which reflect differences among participants, are shown as error bars in Figure 6A. They increase with Δ up to ± 160 ms and then decrease. Figure 6B shows a very similar pattern for the average between-trials standard deviations of the raw asynchronies, which were computed for each sequence position across 10 trials and then averaged across positions 12–21. The maximum variability at $\Delta = \pm 160$ ms was quite substantial and suggests considerable instability. Unexpectedly, the variability was greater at the larger pitch separation. A repeated measures ANOVA on these data, with the same design as the preceding analysis (but with the data for negative Δ values reversed only in order, not in sign), yielded significant main effects of pitch separation, $F(1, 7) = 12.4, p < .01$, of Δ magnitude, $F(4, 28) = 134, p < .0001, \varepsilon = .48$, and of direction, $F(1, 7) = 7.1, p < .04$, with variability being somewhat larger on the negative side.

The assignment of the high and low pitches to the target and distractor sequences made some difference, as can be seen in Figure 7. On the negative side, at Δ values of -80 ms and -160 ms, the distractor effects were smaller when the target was low than when it was high. This was true at both pitch separations. On the positive side, pitch assignment made no difference when the pitch separation was small, but it did seem to make a difference at the large pitch separation, where the distractors had no effect at all when the target was low-pitched. In the ANOVA, however, the four-way interaction that would have reflected this pattern of results was not significant, $F(4, 28) = 2.1, p < .16, \varepsilon = .53$. The only significant effect involving target pitch was the Target Pitch × Magnitude interaction, $F(4, 28) = 4.5, p < .03, \varepsilon = .52$, which indicated that lower pitched targets showed smaller distractor effects at the two largest magnitudes of $|\Delta|$ in the design (80 ms and 160 ms). Handel and Lawson (1983), in a task requiring tapping to the perceived beat of polymetric patterns composed of isochronous sequences differing in pitch, found that participants had a strong bias to tap with the lower tones, which is consistent with the present, rather weak effect.[10]

In summary, Experiment 2 showed that a periodic distractor sequence has a strong and apparently unavoidable influence on the accuracy of synchronization with a target sequence. This influence can be described as the cumulative phase attraction effect of repeated distractor tones. Unexpectedly, however, there was a strong asymmetry, with leading distractor tones exerting much greater phase attraction (often leading to complete phase capture) than lagging distractor tones. Variability of asynchronies was highest in the region where phase attraction was waning. Pitch separation had no significant effect on asynchronies, but variability was uniformly higher at the larger pitch separation.

Experiment 3

This experiment investigated the effect of distractor sequences that differed in tempo as well as in pitch from the target sequences. Thus, the relative phase of the two sequences changed quasi-continuously. The phase attraction exerted by the distractor tones was expected to be evident in periodic modulations of the asynchronies. The distractor sequence was either faster or slower than the target sequence. In the first case, the relative phase decreased steadily (within its normalized range from -0.5 to 0.5), and distractor tones approached target tones from the positive side. In the second case, the relative phase increased steadily, and distractor tones approached target tones from the negative side. Given that Experiment 2 showed that phase attraction is much stronger on the negative than on the positive side, it was predicted that faster

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[9] A third possible measure of variability, the average within-trial standard deviation of the asynchronies, was not calculated but probably would have shown a similar pattern.

[10] In the analysis of the between-trials standard deviations, the Pitch Separation × Target Pitch interaction reached significance, $F(1, 7) = 10.5, p < .02$, but seemed to represent a spurious effect.

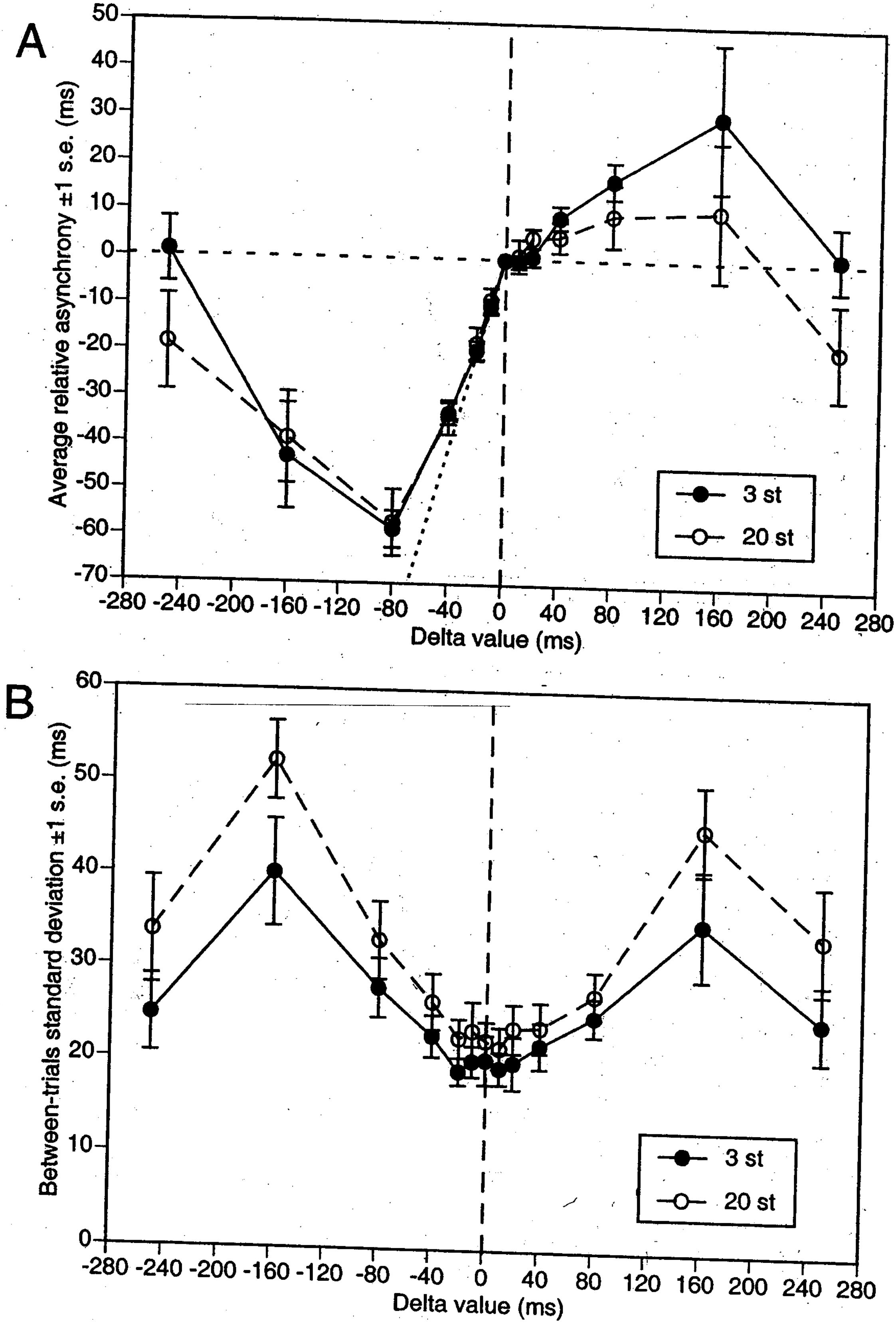

Figure 6. Average relative asynchronies (Panel A) and average between-trials standard deviations (Panel B) as a function of Δ value for two pitch separations in Experiment 2, with between-participants standard error bars. st = semitone.

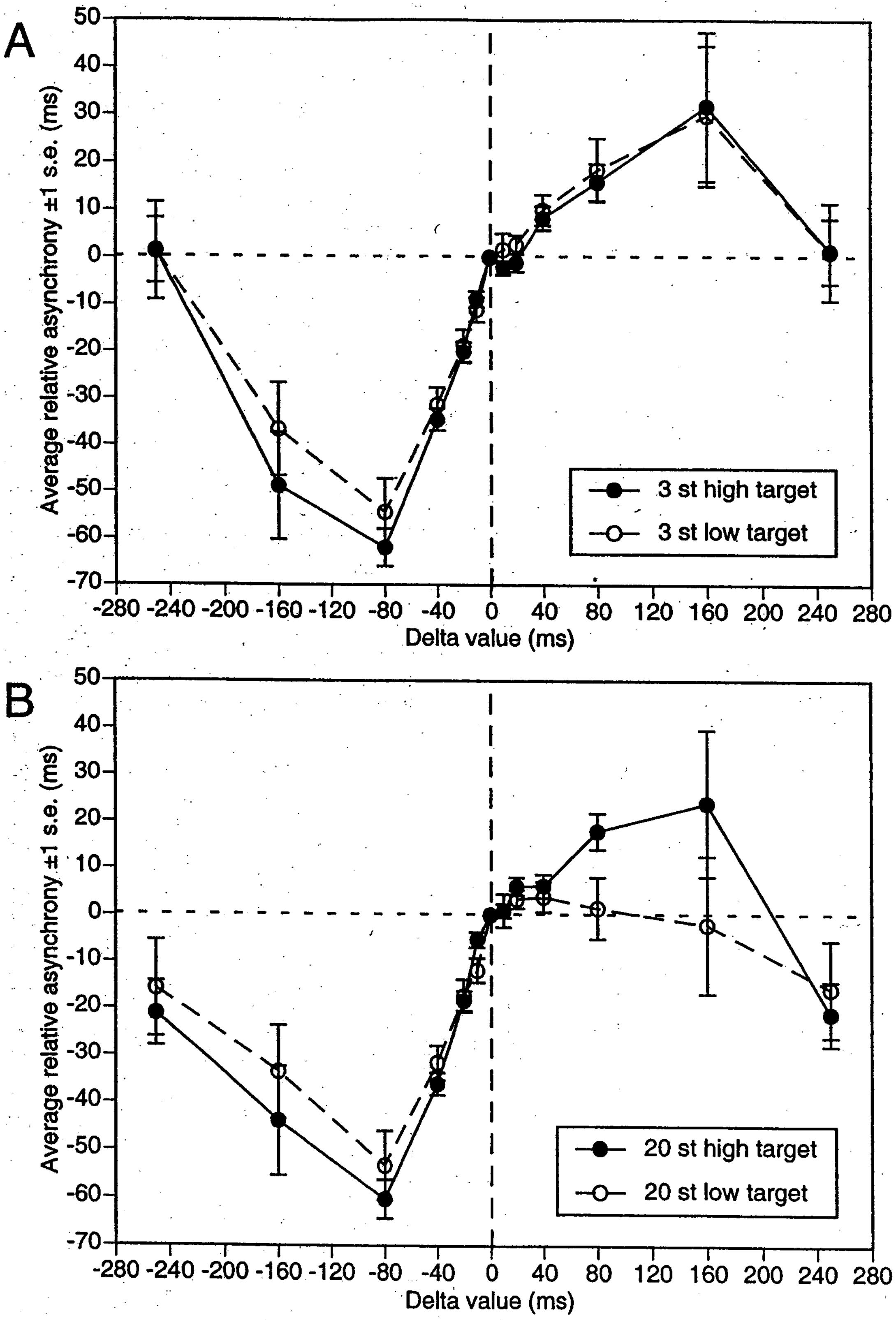

Figure 7. Average relative asynchronies as a function of target–distractor displacement (Δ) for high- and low-pitch target sequences at (Panel A) small and (Panel B) large pitch separation in Experiment 2, with between-participants standard error bars. st = semitone.

distractor sequences would have a stronger effect than slower distractor sequences because the former would pull the taps away from the target tones and then release them as the relative phase became more and more negative, whereas the latter would begin to attract the taps but then push them back toward the target tones as the relative phase became less and less negative.

Method

Participants. Seven of the 8 participants (4 women, 4 men) were the same as in Experiment 2. Replacing a female postdoctoral researcher, the new participant was a male volunteer, 27 years old, who had no musical training.

Materials. Each trial consisted of interleaved target and distractor sequences that differed in pitch and in tempo. The pitch difference was either 3 st or 20 st, with the higher pitch sequence being either the target or the distractor sequence. The pairs of pitches were the same as in Experiment 2. One sequence (either target or distractor) had IOIs of 500 ms whereas the other sequence had IOIs of 550 ms. As in Experiment 2, the first four tones in a trial were target tones. The distractor sequence started either simultaneously with the fifth target tone (in phase) or 250 ms later, in (approximate) antiphase. The temporal offset between the two sequences (Δ) changed in increments or decrements of 50 ms and returned to its initial value after 10 tones of the slower sequence and 11 tones of the faster sequence had occurred. Each trial comprised two such complete cycles. There were 16 trials altogether (2 tempi × 2 pitch distances × 2 pitch assignments × 2 starting phases), which were presented eight times in nonrandom balanced orders (blocks), such that all but 2 successive trials differed in the tempo of the target sequence. The equipment was the same as in Experiments 1 and 2.

Procedure. Participants came for one session. Their task was to tap in synchrony with the target sequence (the one that started earlier), beginning with the second tone, and to ignore the distractor sequence. All other aspects of procedure were the same as in the earlier experiments.

Results

The task was not easy. In a number of trials, the asynchronies between taps and target sequence tones exhibited drift that exceeded half the target sequence IOI duration, and occasionally, other irregularities, such as stops and starts, occurred. The percentages of these unsuccessful trials are shown in Table 1. It is evident that they were highest when the target sequence tempo was slower than the distractor sequence tempo and when, in addition, the pitch separation was small. Target pitch also had an effect, with unsuccessful trials being less frequent when the target pitch was low, at both pitch separations. Closer inspection of the unsuccessful trials revealed that, in trials with slow targets and 3-st pitch separation, the asynchronies usually exhibited linear drift of about −50 ms per tap, which indicates full capture of the taps by the distractor sequence. In other words, participants often lost track of the target sequence and synchronized their taps with the distractor sequence instead. When drift occurred in the other conditions, it was usually less extreme, indicating mere instability or confusion. There were also large individual differences, with some participants having more trouble with the task than others.

Table 1
Percentages of Unsuccessful Trials in Experiment 3

T and D pitch	T and D IOIs (ms)	Pitch separation 3 st	20 st
High/low	500/550	16.4	13.3
Low/high	500/550	8.6	2.3
High/low	550/500	52.3	9.4
Low/high	550/500	32.8	4.7

Note. T = target; D = distractor; IOI = interonset interval; st = semitones.

In successful trials, participants consistently stayed with the target sequence, but their asynchronies nevertheless varied systematically as a function of Δ. The asynchronies were recalculated relative to the asynchrony at the point where the distractor sequence started (i.e., the fourth tap). These relative asynchronies, averaged over each participant's successful trials and then across participants, are shown in Figure 8. Between-participants standard errors have been omitted in the figure because they were rather large, especially at the 3-st separation (as large as 25 ms in some cases). Nevertheless, it is clear that the asynchronies were systematically modulated by the distractor sequence. The upper and lower panels show the data for fast (500-ms IOI) and slow (550-ms IOI) target sequences, respectively. Two pairs of functions are shown in each panel, for initial in-phase and antiphase relationships, respectively, with the two functions in each pair representing the two pitch separations. The vertical dotted lines and the symbols on the abscissa indicate when target and distractor tones coincided, with the *0* symbols referring to the sequences that were initially in phase, and the *X* symbols referring to the sequences that were initially in antiphase.

The first thing to note is that the relative asynchronies were generally negative. This is consistent with the phase attraction asymmetry observed in Experiment 2: A distractor sequence exerts stronger phase attraction when it leads the target sequence (making asynchronies more negative) than when it lags. In all conditions, the asynchronies were modulated in a roughly sinusoidal fashion. Some of the functions also show slow positive drift (i.e., a gradual slowing of the tapping tempo). When the target sequence was faster than the distractor sequence (Figure 8A), the relative asynchronies were most negative just before the point at which the target and distractor sequences were in phase (*0* or *X* on the abscissa) and least negative or even positive when the two sequences approached the antiphase relationship. When the target sequence was slower than the distractor sequence (Figure 8B), the pattern was reversed, and the modulations tended to be larger.

These patterns can be explained in terms of the phase attraction effects demonstrated in Experiment 2. When the distractor sequence was slower than the target sequence (Figure 8A), the relationship of distractor tones to successive target tones was one of decreasing leads and increasing lags. Thus, the distractor tones exerted strong negative phase attraction until they were in phase and weak positive phase attraction as they moved toward antiphase. When the distractor sequence was faster than the target sequence (Figure 8B), the relationship of distractor tones to successive target tones was one of decreasing lags and increasing leads. Thus, the distractor tones exerted weak positive attraction until they were in phase and strong negative attraction as they moved toward antiphase. Because the strongest phase attraction occurred as the distractor tones moved away from the target tones, synchronization with the target sequence was destabilized more in this condition, and in fact, the distractor tones often captured the taps completely (Table 1).

Although capture was much more frequent when the pitch separation was small, it is noteworthy that, on those trials where

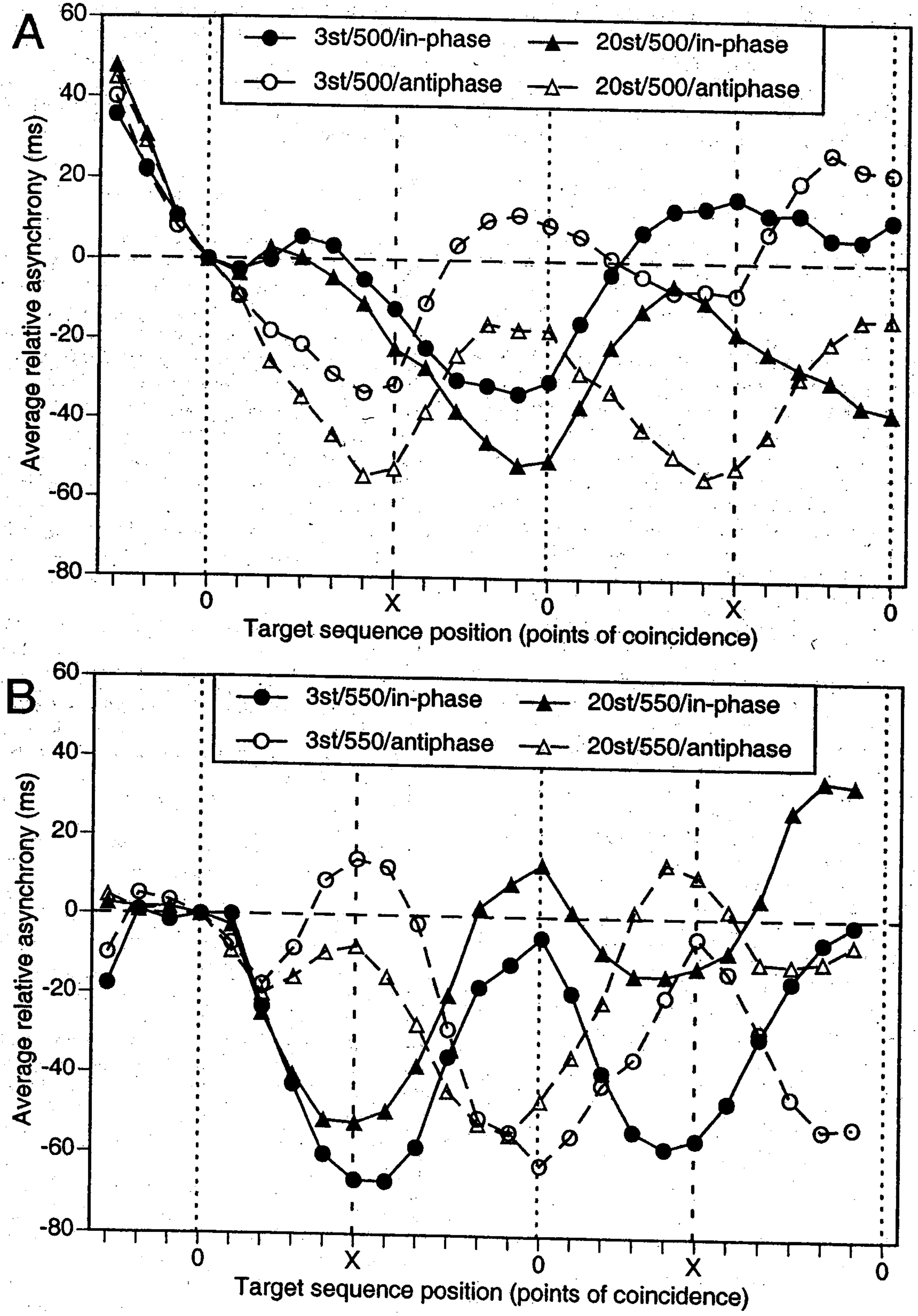

Figure 8. Average relative asynchronies in successful trials of Experiment 3 as a function of target sequence position for (Panel A) fast (interonset interval [IOI] = 500 ms) and (Panel B) slow (IOI = 550 ms) target sequences, each at two target–distractor pitch separations (3 semitones [st], 20 st), and two starting phases (in-phase, antiphase). The 0 and X symbols on the abscissa indicate the points where target and distractor tones coincided (i.e., where the two sequences were in phase) for initially in-phase and antiphase sequences, respectively.

capture did not occur (Figure 8), the modulation of the asynchronies was similar at small and large pitch separations. This suggests that an additional cognitive or attentional factor, sensitive to pitch differences, may have been involved in capture (see General Discussion). Although the functions for the 3-st and 20-st conditions did not coincide in any of the four conditions defined by target sequence tempo and initial phase relationship, their difference seemed to be more one of degree of slow drift than of degree of modulation. When the target sequence was fast (Figure 8A), the relative asynchronies showed more positive drift at the 3-st than at the 20-st separation, but when the target sequence was slow (Figure 8B), the opposite was true. The pitch of the target sequence also seemed to affect positive drift (not shown in Figure 8). These effects are difficult to interpret.

According to the results of Experiment 2, one might have expected the strongest phase attraction effects to occur at a negative relative phase between target and distractor sequences. However, the minima in the functions of Figure 8 are close to the in-phase points, at which there cannot be any phase attraction. This probably derives from the continuously changing phase relationship between target and distractor sequence, which made the attractor effects cumulative and behavioral effects lag behind. Thus, the modulations seen in Figure 8 lag one or two steps (of 50 or 55 ms) behind the actual phase attraction effects.

The systematic modulation of the asynchronies is not in need of statistical support because every participant showed the effect on every successful trial. To assess the statistical reliability of other differences, I computed average relative asynchronies and their standard deviations across entire trials (except for the target sequence lead-in) and subjected them to separate repeated measures ANOVAs, with the variables of target pitch, target tempo, pitch separation, and starting phase. Only two effects reached significance for the mean asynchronies. One was the Pitch Separation × Target Tempo interaction, $F(1, 7) = 14.6$, $p < .007$: At the fast target tempo, the asynchronies were less negative at the small than at the large pitch separation, whereas it was the other way around at the slow target tempo. (Compare circles and triangles in Figure 8.) The other effect (not shown in Figure 8) was a marginally significant Target Tempo × Target Pitch interaction, $F(1, 7) = 5.7$, $p < .05$: When the target tempo was slow, the asynchronies were less negative for low-pitched than for high-pitched targets, but there was a tendency in the opposite direction when the target tempo was fast. The main effect of pitch separation was nonsignificant, $F(1, 7) = 0.5$.

The standard deviations reflect both the degree of modulation and any slow drift of the asynchronies; no attempt was made to separate these two components. The main effect of pitch separation was nonsignificant, $F(1, 7) = 3.0$, $p < .13$. Three other effects reached significance, however. The main effect of target tempo, $F(1, 7) = 11.7$, $p < .02$, confirmed that the asynchronies were modulated more strongly at the slow than at the fast target sequence tempo. The main effect of target pitch, $F(1, 7) = 8.5$, $p < .03$, indicated stronger modulation when the target pitch was high than when it was low. A marginally significant Pitch Separation × Target Tempo × Starting Phase interaction, $F(1, 7) = 5.8$, $p < .05$, is difficult to interpret.

In summary, Experiment 3 demonstrated that strong phase attraction effects are exerted by distractor sequences whose tempo differs from that of the target sequence. These effects are reflected in periodic modulations of the asynchronies. The modulations tended to be larger when the target sequence was slower than the distractor sequence. When, in addition, the pitch separation was small, complete capture by the distractor sequence often occurred. On those trials where participants managed to stay with the target sequence, pitch separation did not have a main effect, but it interacted with target tempo.

Experiment 4

The effects discovered in Experiment 3 were explored further in Experiment 4. In Experiment 3, the absolute target sequence tempo was confounded with the tempo relationship between target and distractor sequences. The main purpose of Experiment 4 was to vary these two factors independently to determine which of them was mainly responsible for the greater difficulty of the combination of slow target sequence with fast distractor sequence. In addition, the length of the sequences was extended to comprise four complete cycles of each target–distractor combination, and a new response device was used that provided some auditory feedback. Because the initial phase relationship of target and distractor sequences did not seem to play an important role in Experiment 3, only an in-phase starting condition was used in Experiment 4.

Method

Participants. The participants were 10 paid volunteers (8 women, 2 men) who had not participated in Experiment 3; in addition, I also participated, as usual. Most volunteers had only limited tapping experience from three sessions of a different experiment; only one had more extensive experience and had also participated in Experiment 1. However, they were all well motivated because they had volunteered to participate in many experiments of this kind. Musical training ranged from a few years to professional level. One volunteer was, like myself, in his 50s; the others were in their 20s.

Materials. There were two target sequence tempi, fast (IOI = 500 ms) and slow (IOI = 600 ms). Each type of target sequence was paired with each of two distractor sequences, one faster by 10% and the other slower by 10%. Thus, the IOIs of the distractor sequences for the fast target sequence were 450 ms and 550 ms, whereas those of the distractor sequences for the slow target sequence were 540 ms and 660 ms. In each of the resulting four conditions, there were two degrees of pitch difference (3 or 20 st) and two pitch assignments, the pitches being the same as in Experiment 3.[11] Thus, there were 16 different conditions altogether. Each trial began with six tones of the target sequence. The distractor sequence always started in phase with the seventh tone of target sequence. Each trial continued for four complete target–distractor cycles (i.e., 4 × 9 = 36 target tones when the distractor sequence was faster and 4 × 11 = 44 target tones when the distractor sequence was slower). Each block contained a different random order of the 16 trials. One practice block and six test blocks were presented.

Procedure. The task was the same as in Experiment 3. However, instead of tapping on a quiet MIDI controller, participants used a newly acquired Roland SPD-6 percussion pad (12 × 9 × 2 in. [30.48 × 22.86 × 5.08 cm]) that they held on their lap.[12] The unit has six individual rubber pads (3.5 × 3 in. [8.89 × 7.62 cm]) arranged in two rows of three. Its sensitivity was set to the manual (as opposed to drumstick) mode. Participants tapped with the right index finger (in one case, with the middle

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[11] Due to an apparent oversight, the low-pitched tones were not reduced in intensity (key velocity) and thus were louder than the higher pitched tones. However, as will be seen, this was of little consequence.

[12] Only I, as the first participant, still used the MIDI controller.

finger) on the center pad of the upper row. Some participants rested their wrist and other fingers on the surface of the pad and tapped in the center by moving the index finger only; others preferred to tap from above by moving the hand and elbow of the unsupported 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.) The occurrence of a tap was recorded when the finger touched the pad. Participants were instructed to tap with sufficient force for the taps to be registered, and there were very few missing taps. The session was self-paced: Participants clicked a button on the computer screen with the mouse to start a block of trials and then pressed the space bar on the computer keyboard for subsequent trials, which started 3 s later. Participants started tapping with the third target tone.

Results

As in Experiment 3, unsuccessful trials (defined as those containing asynchronies exceeding half the target sequence IOI or, rarely, other anomalies) were identified first. Table 2 shows the percentages of these trials. All four independent variables seemed to have an effect. (No statistical analysis was conducted on these data.) Most obviously, there were few unsuccessful trials when the pitch separation between target and distractor tones was large, whereas there were many at the small pitch separation. At small pitch separations, unsuccessful trials were more common when the target pitch was higher than the distractor pitch. They were also more frequent when the target tempo was slow than when it was fast. When the target tempo was fast, distractor tempo had little effect but when the target tempo was slow and if the target pitch was high, unsuccessful trials were twice as frequent when the distractor sequence was faster than when it was slower than the target sequence.

Average asynchronies were computed from the successful trials. They are shown in Figure 9 for target–distractor combinations in which the distractor sequence tempo was faster than the target sequence tempo, and in Figure 10 for combinations in which the distractor sequence tempo was slower than the target sequence tempo. In this experiment, the asynchronies were not recalculated relative to the point at which the distractor sequence began.[13] As in Experiment 3, all asynchronies were overwhelmingly negative, even relative to the first in-phase point. Strong modulation of the asynchronies was again evident, as well as slow positive drift in some conditions. The availability of auditory feedback from the taps obviously did not prevent these effects. As expected, the functions in Figure 9 show maxima near points of coincidence (zero relative phase), whereas the functions in Figure 10 show minima near those points. Although the modulation of the asynchrony functions is roughly sinusoidal, it is not perfectly symmetric, especially in Figure 10. The slow descent to the minima in those latter functions, which reflects the growing phase attraction of the distractor tones as they approach zero relative phase from the positive side, is followed by a rapid rise, which reflects the weak phase attraction of distractor tones that lag behind the target tones. A weaker asymmetry of the opposite kind can be discerned in the functions of Figure 9.

Table 2
Percentages of Unsuccessful Trials in Experiment 4

T and D pitch	T and D IOIs (ms)	Pitch separation 3 st	Pitch separation 20 st
High/low	500/450	43.9	0.0
	500/550	42.4	3.0
Low/high	500/450	10.6	0.0
	500/550	15.2	3.0
High/low	600/540	68.2	3.0
	600/660	34.8	3.0
Low/high	600/540	25.8	3.0
	600/660	21.2	1.5

Note. T = target; D = distractor; IOI = interonset interval; st = semitones.

The functions for the different tempo combinations and pitch assignments show large differences in mean asynchrony and smaller ones in modulation depth. To assess the reliability of these differences, I conducted repeated measures ANOVAs on the mean asynchronies and on the standard deviations of the asynchronies in successful trials.[14] The variables in the ANOVAs were target tempo (fast, slow), distractor tempo relative to target tempo (faster, slower), pitch separation (small, large), and pitch assignment (target higher or lower than distractor). There were nine missing data points in this design because some participants had no successful trials in some conditions. Eight of these conditions involved high-pitch targets combined with lower pitch distractors at a small pitch separation; one involved the reverse pitch assignment at a small pitch separation. Each ANOVA was carried out twice, the first time with all participants included and with the missing cells filled in by duplicating the values for the corresponding condition with the reverse pitch assignment, and the second time after excluding the 5 participants in whose data the missing data points occurred. To be considered reliable, effects had to be significant in both analyses. Usually, only the results of the first analysis are mentioned.

There was a significant main effect of target tempo on mean asynchronies, $F(1, 10) = 26.8$, $p < .0005$: Asynchronies were substantially more negative for slow target sequences (−58 ms) than for fast target sequences (−37 ms). There was also a significant main effect of relative distractor tempo, $F(1, 10) = 29.9$, $p < .0004$: Asynchronies were more negative when the distractor sequence was faster than the target sequence (−59 ms) than when it was slower than the target sequence (−36 ms). There was a weak interaction between these two variables, $F(1, 10) = 7.4$, $p < .03$, which did not reach significance in the second ANOVA: Asynchronies were especially negative when a slow target sequence was paired with a faster distractor sequence (Figure 9B). Furthermore, there were two highly significant interactions, one between relative distractor tempo and pitch separation, $F(1, 10) = 30.7$, $p < .0003$, and the other between these two variables and pitch assignment, $F(1, 10) = 31.4$, $p < .0003$. The two-way interaction indicated that relative distractor tempo had no effect on mean asynchronies when the pitch separation between target and dis-

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[13] This was not done because the measurement of absolute asynchronies was more accurate on the new equipment. It made little difference for the comparisons of the functions. Only the last four lead-in asynchronies are shown in the figures.

[14] For reasons of computational convenience, the standard deviations were computed here after averaging across all successful trials in each condition for each participant. (In Experiment 3, standard deviations were computed for individual trials and then were averaged.)

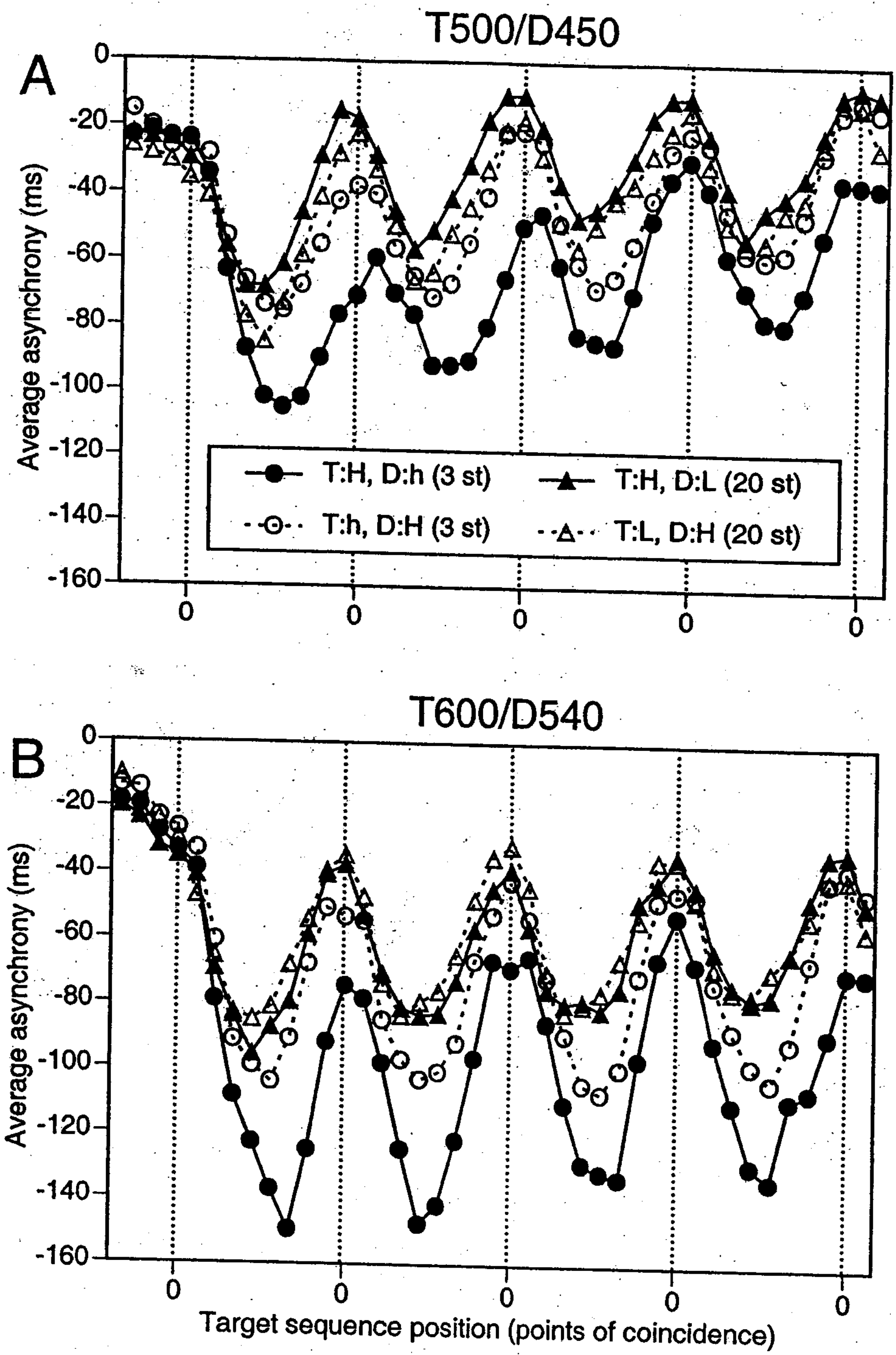

Figure 9. Average relative asynchronies in successful trials of Experiment 4 as a function of target (T) sequence position for (Panel A) fast (T500) and (Panel B) slow (T600) target sequences with faster distractor (D) sequences (D450 and D540, respectively). For each target–distractor tempo combination, the functions for the four pitch assignments are shown; in the legend, the target pitch is followed by the distractor pitch. Points of coincidence (zero relative phase) are indicated along the abscissa. H = high; h = less high (3 semitones [st] lower); L = low (20 st lower).

tractor sequences was large, whereas at a small pitch separation, asynchronies were more negative when the distractor sequence was faster than when it was slower than the target sequence. The triple interaction further qualifies this finding: The effect of relative distractor tempo on mean asynchronies at a small pitch separation was larger when the distractor tones had a lower pitch than the target tones. At the same time, there was a crossover interaction within the conditions with large pitch separation: When the

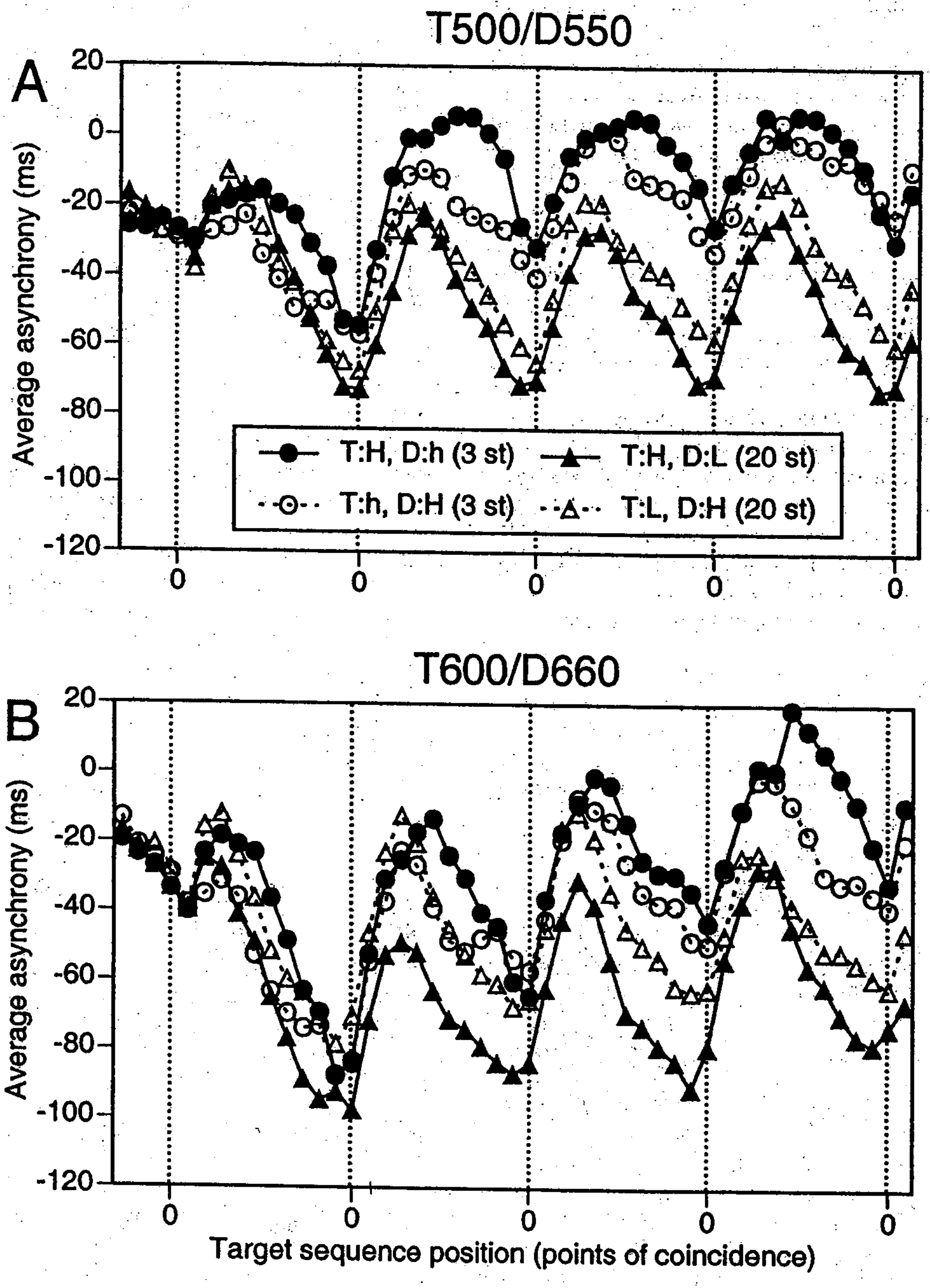

Figure 10. Average relative asynchronies in successful trials of Experiment 4 as a function of target (T) sequence position for (Panel A) fast (T500) and (Panel B) slow (T600) target sequences with slower distractor (D) sequences (D550 and D660, respectively). For each target–distractor tempo combination, the functions for the four pitch assignments are shown; in the legend, the target pitch is followed by the distractor pitch. Points of coincidence (zero relative phase) are indicated along the abscissa. H = high; h = less high (3 semitones [st] lower); L = low (20 st lower).

target tones were higher in pitch than the distractor tones, asynchronies were more negative when the distractor sequence was slower than when it was faster than the target sequence, but the reverse held when the target tones were lower in pitch than the distractor tones. All these differences can be seen clearly in Figures 9 and 10.

The results for the standard deviations were of main interest. The most striking effect was a main effect of target tempo, $F(1, 10) = 27.8$, $p < .0005$: The asynchronies were more strongly modulated when the target tempo was slow than when it was fast. By contrast, the main effect of relative distractor tempo was not significant, $F(1, 10) = 1.6$, $p < .23$. This result answers the main question posed in this experiment with regard to the two variables that had been confounded in Experiment 3: The degree of modulation of the asynchronies evidently reflects more the target sequence tempo (also, the rate of tapping) than the tempo relationship between target and distractor sequences.

In addition to this highly reliable effect, there were three weaker effects, one of which (the main effect of pitch assignment) was nonsignificant in the second analysis. It indicated somewhat greater modulation when the target pitch was higher than the distractor pitch. This effect was more pronounced when the target tempo was slow, which resulted in a significant interaction, $F(1, 10) = 6.3$, $p < .04$. Finally, and most importantly, there was a significant main effect of pitch separation, $F(1, 10) = 7.7$, $p < .02$: Modulation was stronger at the small than at the large pitch separation. This result suggests that the strength of phase attraction is not completely independent of pitch separation after all.

A considerable amount of variability, however, was contributed by slow drift, which is not a phase attraction phenomenon. To separate this drift from the systematic modulation of the asynchronies, I performed linear regressions on the average asynchrony functions of each participant in each condition and recalculated the standard deviations of the asynchronies from the residuals. Repeated measures ANOVAs, with the same design as before, were performed both on the slopes of the regression lines and on the standard deviations.

The grand average slope was significantly greater than zero, $F(1, 10) = 8.95$, $p < .02$, although this difference did not reach significance in the second ANOVA (on the 6 participants whose data were complete). The slopes were significantly larger when the distractor sequence was faster than when it was slower than the target sequence, $F(1, 10) = 5.6$, $p < .04$, and when the pitch separation was small than when it was large, $F(1, 10) = 8.2$, $p < .02$. In addition, there was an interaction between these two variables, $F(1, 10) = 16.0$, $p < .003$, although it fell short of significance in the second ANOVA. The interaction indicated that slow drift (a slowing of the tapping tempo) occurred when the pitch separation was small and also when the pitch separation was large and the distractor sequence tempo was fast but that there was no slow drift at all when pitch separation was large and the distractor sequence tempo was slow.

The analysis of the standard deviations of the detrended data yielded two effects that were clearly significant in both ANOVAs. (Several additional effects reached significance only in the first ANOVA and therefore are not discussed.) The two reliable effects were the main effects of target sequence tempo, $F(1, 10) = 49.4$, $p < .0001$, and of pitch separation, $F(1, 10) = 11.8$, $p < .007$. Thus, this analysis confirmed the previous finding of larger variability when the tapping rate was slow and when the pitch separation between target and distractor sequences was small, and it showed that these effects were mainly due to the amplitude of the systematic modulation of the asynchronies.[15]

In summary, Experiment 4 replicated the main findings of Experiment 3, even though a response device providing auditory feedback was used. This suggests that the distractor effects are unavoidable and relatively independent of the availability of auditory feedback. The experiment also showed that the greater difficulty of the combination of a slow target sequence tempo with a fast distractor tempo is due to the target sequence tempo, not to the tempo relationship between the two sequences. Unexpectedly, the modulations caused by the distractor sequence were somewhat larger when the pitch separation was small.

General Discussion

This study addressed two main issues: the obligatory nature of phase attraction in sensorimotor synchronization and the relative insensitivity of this attraction to pitch differences that are known to affect perceptual organization.

Obligatory Phase Attraction

To investigate the obligatory nature of phase attraction, three kinds of distractor were presented while participants tried to stay in synchrony with an isochronous target sequence: single distractor tones (Experiment 1), repeated distractor tones at various fixed phase relationships (Experiment 2), and repeated distractor tones at continuously changing phase relationships (Experiments 3 and 4). In this way, the present research went beyond earlier studies in which obligatory phase correction was investigated by introducing perturbations in the target sequence itself (see, e.g., Repp, 2002a) and where an automatic PCR was less surprising because a temporal expectation was violated by the perturbation. Here, it was predicted that, even when all target tones occurred at the expected times, an extraneous sound occurring in their vicinity would automatically engage the phase correction process and thereby perturb the timing of the motor activity. This prediction was strongly supported by the results of all four experiments.

Experiment 1 showed that the involuntary PCR elicited by a distractor tone occurring close to a target tone was on average about half as large as the PCR elicited when a target tone was shifted by the same amount. This suggested that the target and distractor tones were given equal weight by the automatic phase correction process. However, when the temporal separation between target and distractor tones was greater than about 100 ms (20% of the IOI), the PCR decreased or disappeared, indicating that the target tone predominated. Experiment 1 was not designed to determine the precise shape of this phase attraction function, but the region of target–distractor integration seemed to extend further on the negative side (distractor leading) than on the positive side (distractor lagging). Because the target sequence tempo was not varied, it remains unclear whether the integration region should be characterized in terms of absolute temporal separation or relative phase.

The phase attraction exerted by single distractor sounds was weak, albeit significant. Much stronger phase attraction effects were obtained in Experiment 2 with periodic distractor sequences, which shows that the effects of successive distractor tones reinforce each other. The cumulative nature of the effects is easy to understand because the PCR to a distractor tone reduces the temporal distance between that tap and the next distractor tone, so that the phase attraction effect exerted by that tone is increased.

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[15] It could be argued that the analysis was biased in favor of obtaining an effect of pitch separation because the standard deviations were calculated after averaging over individual trials in each condition. Because fewer successful trials went into the average in the conditions with small pitch separation, the average asynchronies were likely to be more variable than in conditions with large pitch separation. However, this argument applies more to unsystematic variability than to the large systematic modulation that presumably dominated the variability measure. Because the analysis was carried out manually in a spreadsheet program, it would have been prohibitively time-consuming to deal with individual trials.

This increasing attraction can lead to the taps being synchronized with the distractor sequence instead of the target sequence (i.e., capture). An unexpected asymmetry, not readily predicted from the results of Experiment 1 or of earlier perturbation studies, was discovered: Leading distractor tones exerted much stronger phase attraction than did lagging distractor tones. Capture was the rule at negative Δ values (again, up to about 100 ms, or 20% of the IOI) but rarely occurred at positive Δ values. When the onsets of target and distractor tones were separated by 20 ms or less, synchronization always occurred with the leading tone, which may be attributed to fusion of the two tones. However, the asymmetric phase attraction at greater separations, where target and distractor tones were perceptually distinct, cannot be explained in this way.

As a participant, I was not aware that I was often synchronizing my taps with the distractor sequence. (Presumably, this was also true for the other, less experienced participants, though they were not interrogated.) This informal observation suggests that phase attraction is independent of attention: Even though attention was focused on the target sequence, the taps migrated toward the distractor sequence. In that connection, it should also be remembered that the taps were silent (or faintly noisy for some participants). Phase attraction effects may well have been smaller if a feedback tone had been associated with the taps, so that an auditory rather than a cross-modal criterion of synchrony could have been used.[16]

A recent experiment by Aschersleben and Bachmann (2001) raises a question that may also be asked about the results of Experiment 2. Aschersleben and Bachmann asked participants to synchronize finger taps with the first or second of two visual stimuli that had various IOIs (up to 90 ms) and were repeated cyclically. In some conditions, the first stimulus was masked by the second (metacontrast), but in other conditions, both stimuli were visible. Synchronization with the first stimulus (when it was not masked) was unaffected by the presence of the second stimulus, but taps intended to be synchronized with the second stimulus migrated toward the first stimulus by about 50% of the IOI, even when the first stimulus was invisible. The authors interpreted their findings as indicating a predating (i.e., accelerated processing) of the second stimulus, due to priming by the first stimulus. That is, they were assuming that participants were in fact synchronizing their taps with the target stimulus, which they perceived as occurring earlier in time.

Correspondingly, it could have been the case in Experiment 2 that target tones were perceived as occurring earlier when they were preceded by distractor tones and that participants synchronized their taps with these predated target tones. This might account for participants' lack of awareness of capture, and it would also explain the asymmetry of the phase attraction. However, there is little doubt that tones separated by 80 ms, say, are perceived as clearly separated in time, even though the results of Experiment 2 suggest that the target tones were predated so as to almost coincide with leading distractor tones at that separation. Predating thus would have to be independent of conscious perception, contrary to what Aschersleben and Bachmann (2001) seem to have assumed; it would have to occur in a system that controls action timing only. A functional separation of information for perception and action, which has been well documented in vision (see, e.g., Goodale & Humphrey, 1998; Neumann, 1990), may well also exist in audition (see Repp, 2000, 2001a, 2002b). However, positive phase attraction effects (which were smaller but nevertheless present) cannot be explained in this way, and the complete capture obtained at negative Δ values up to −100 ms shows the presumed predating to be much stronger in audition than in vision. An alternative interpretation that I prefer is that the times of occurrence of the target and distractor tones are registered accurately but engage the same action timing process (viz., phase correction). The bias favoring the leading tone could be attributed simply to temporal precedence. Rather than assuming that participants synchronized their taps with predated target stimuli, it is proposed here that participants could not help synchronizing with distractor stimuli instead of, or in addition to, the intended target stimuli. In other words, action timing is determined by a mixture of two sources of accurate temporal information rather than by a single source of inaccurate information resulting from the perceptual interaction of successive stimuli. Further experiments attempting to distinguish more rigorously between these two interpretations would be worthwhile.

The results of Experiment 2 are also related to several studies that have investigated the coordination of bimanual movements at various phase relationships. When finger taps of each hand are synchronized with interleaved visual pacing sequences representing various phase relationships (Tuller & Kelso, 1989) or when tapping continues after such pacing (Yamanishi, Kawato, & Suzuki, 1980), the phase relationship of the hands tends to be distorted in the direction of the more stable in-phase or antiphase relationships (whichever is closer). Also, variability is lowest in the in-phase and antiphase conditions, very much as in Experiment 2 (Figure 6B). Kelso (1995) dubbed this the "seagull effect" (p. 164). These results have been modeled in terms of coupled nonlinear oscillators representing the two hands. Similarly, the paradigm of Experiment 2 could be regarded as involving coupled perceptual or sensorimotor oscillators (Large, 2000; Large & Jones, 1999). Phase attraction would then depend on the strength of coupling and the specific phase relationship between the oscillators. This conception does not explain the observed asymmetry unless an asymmetric coupling function is assumed. Nevertheless, dynamic models of this kind deserve further consideration because they may provide appropriate formal characterizations of the cumulative effect of repeated distractor tones.[17]

Semjen and Ivry (2001) recently used interleaved auditory sequences of different pitch, similar to those used in Experiment 2, as well as visual sequences, to pace finger tapping. They obtained similar results for bimanual and unimanual tapping, which led them to argue against an explanation in terms of bimanual coupling dynamics and in favor of cognitive (rhythm-based) timing control. Their unimanual condition, however, required tapping to the compound rhythm of both sequences (a task requiring perceptual integration) and thus was different from the present task, which required tapping to one sequence only (favoring perceptual segregation). Both tasks have in common that they pose difficulties of rhythmic timing control that do not originate in the coupling of the two hands. Apart from that, however, they are quite unlike each other: In Semjen and Ivry's task, poor synchronization with a

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[16] However, auditory feedback seemed to make little difference when the target–distractor phase relationship was continuously changing (Experiment 3 vs. Experiment 4).

[17] The late Jeff Pressing suggested, as a reviewer of this article, that the present data could be modeled using the discrete control equation of his referential behavior theory (Pressing, 1999).

complex rhythm occurred because taps were attracted toward perceived or imagined rhythms having simple interval ratios. In the present task, poor synchronization with a simple component of a complex rhythm occurred because taps were attracted toward other components of the rhythm. Thus, the phase attraction effects obtained in the Semjen–Ivry task are top-down in nature (similar to those observed in purely perceptual tasks), whereas those in the present task are bottom-up and probably arise at a different processing level.

This difference may explain why the present data show no evidence of increased stability at ratios of 2:1 (or 1:2), which correspond fairly closely to a Δ value of ± 160 ms in Experiment 2. Such stability was observed by Semjen and Ivry (2001) in bimanual and unimanual tapping to compound auditory sequences. However, their sequence tempo was also much slower. Clearly, the effects demonstrated in Experiment 2 need to be explored further by varying the tempo. They may not depend on phase relationships at all but rather may reflect an absolute interval of perceptual integration—a topic that is being pursued in current research.

Experiments 3 and 4 demonstrated that the asynchronies between taps and target sequence tones were strongly and obligatorily modulated by the changing phase relation between the target sequence and a periodic distractor sequence of different tempo. These modulations can be readily explained as the consequence of waxing and waning phase attraction effects, and they also showed a strong asymmetry, consistent with the findings of Experiment 2. The modulations were stronger when the tempo of the target sequence was relatively slow, regardless of the tempo of the distractor sequence. It is known that tapping at a slower tempo leads to more effective phase correction in synchronizing with a single isochronous sequence (Pressing, 1999), presumably because of a reduced "maintenance tendency" (Riley, Santana, & Turvey, 2001; Von Holst, 1973) or "motor persistence" (Repp, 2001a), which results in increased flexibility of timing, increased variability, and increased susceptibility to external influences. In research on bimanual polyrhythmic tapping, it has been observed that the coupling between the hands increases when the tempo is decreased (Peper & Beek, 1998; Peper, Beek, & van Wieringen, 1995a, 1995b). In the present case, the slower tempo of the target sequence probably made the taps more susceptible to phase attraction, even though the range of tempi employed was fairly small.

The results of all four experiments are consistent in showing that attraction to extraneous sounds and especially periodic sequences of sounds is unavoidable in sensorimotor synchronization, even when there is an intact auditory target sequence to synchronize with. Moreover, I (Repp, 2002a) have shown that, even when phase attraction is minimal, namely, when a distractor sequence is in antiphase with a target sequence, a small perturbation in the distractor sequence affects the timing of finger taps synchronized with the target sequence. Thus, the phase correction process seems to be indiscriminately sensitive to the temporal relations between auditory events. However, presumably there are limits to that sensitivity. Will totally unrelated sounds—the beat of background music, hammering on the wall, a door being slammed—attract the phase of finger taps that are synchronized with a metronome? Perhaps not, though this remains to be investigated. The present study examined only the role of a single parameter differentiating target and distractor sounds, namely, differences in pitch.

Insensitivity of Phase Attraction to Pitch Differences

The second main hypothesis addressed by the present experiments was that phase attraction would be completely insensitive to pitch differences between targets and distractors. The results do not support this strong version of the hypothesis, but they are consistent with a weaker version stating that phase attraction is fairly insensitive to pitch differences.

Even though source segregation is not an issue here because all sounds came from the same ostensible source (a digital piano), it is well known that differences in pitch alone can cause perceptual grouping and segregation of auditory streams (Bregman, 1990). Obligatory stream segregation occurs only at rates much faster than were used here, so the present experiments did not address the even stronger hypothesis that phase attraction is independent of obligatory stream segregation. Rather, they addressed the hypothesis that phase attraction is insensitive to pitch differences between sounds that may or may not be perceived as belonging to the same stream. The synchronization task required selective attention to the target sequence and thus encouraged intentional stream segregation, to the extent that this was possible at the relatively slow tempo. A large pitch difference between target and distractor tones can only have facilitated selective attention to the target sequence, and my subjective impression was that it did.

In Experiment 1, the small effects caused by single distractor tones did not show a main effect of pitch separation, but there were two significant interactions involving this variable. One occurred in the control conditions (Conditions 1–3), where a large pitch difference attenuated the PCR caused by a leading distractor tone. The other interaction, which occurred in the experimental conditions (Conditions 4–7), involved three variables and thus was difficult to explain.

In Experiment 2, there was again no main effect of pitch separation, especially in the region of strong phase attraction (leading distractor tones). Although pitch separation did seem to make a difference for some participants when the distractor tones lagged behind the target tones, the interaction was not significant overall. There was an unexpected increase in variability when the pitch separation was large rather than small, regardless of the temporal relationship of the two sequences. This may indicate that perceptual integration of the two sequences into a compound rhythm actually helped synchronization with the target sequence because the distractor sequence was less distracting in that case. When the pitch separation was large, integration into a compound rhythm was more difficult, and rather than facilitating the task by making the distractor sequence easier to ignore, the pitch separation may have made the distractor sequence truly distracting, thereby increasing temporal uncertainty. Perhaps an even larger acoustic difference between target and distractor tones would have led to a decrease in tapping variability.

In Experiments 3 and 4, pitch separation clearly had an effect on the occurrence of capture, that is, synchronization with the distractor sequence instead of the target sequence. In Experiment 3, pitch separation had an effect on capture only when the target tempo was slow, but in Experiment 4, capture was much more frequent at both target sequence tempi when the pitch separation was small. These findings would seem to constitute strong evidence against the hypothesis that phase attraction is insensitive to pitch separation. It could be argued, however, that capture is not due to phase attraction (alone) but rather involves additional cognitive processes that are sensitive to pitch differences. One relatively uninteresting possibility is that, when the pitches of target and distractor sequences were similar, participants may have forgotten which sequence was the target sequence. This interpretation is consistent with the fact that, once capture had occurred, no attempts to return to the target sequence were evident: Participants did not seem to realize that they were synchronizing with the wrong sequence. Nevertheless, I believe that this trivial explanation accounts for only a small proportion of unsuccessful trials. A much more interesting possibility is that capture reflects an involuntary change in the internal timekeeper or oscillator period that governs the tempo of the taps. Just as the distractor tones exert phase attraction according to their temporal distance or relative phase, so the IOIs of the distracter sequence may exert period attraction. Phase correction and period correction are two different processes hypothesized to underlie adaptation in sensorimotor synchronization (Mates, 1994a, 1994b; Repp, 2001b; Semjen, Vorberg, & Schulze, 1998), and there is evidence that period correction is a more cognitive process than phase correction (Repp, 2001b; Repp & Keller, in press). Even though participants did not intend to change their internal period, the IOIs of the distractor sequence may have engaged the period correction process, especially when the two sequences were acoustically similar. Thus, participants may have suddenly switched to tapping at a different tempo but did not realize it because they remained in synchrony with a tone sequence, albeit the wrong one. Capture can also be interpreted as a shift of metrical organization within an inherently polymetric rhythm (cf. Handel & Lawson, 1983) and as such would also be a cognitive phenomenon different from phase attraction. Thus, the effect of pitch separation on the incidence of capture may reflect a different level of processing and does not necessarily contradict the hypothesis that phase attraction is relatively insensitive to pitch separation.

Indeed, in Experiment 3, the main effect of pitch separation was nonsignificant in the analysis of variability in successful trials. In Experiment 4, however, variability was significantly larger when the pitch separation was small than when it was large, in terms both of slow drift and especially of the cyclic modulation of the asynchronies. It is this last result that provides the strongest evidence against the hypothesis that phase correction is completely insensitive to pitch differences. However, even a large pitch separation did not prevent large modulations of the asynchronies in Experiments 3 and 4. Therefore, the conclusion is justified that phase correction is relatively insensitive to pitch differences.

One very reliable but somewhat mysterious finding in both Experiments 3 and 4 was that pitch separation and the relative tempo of the distractor sequence jointly affected the mean asynchronies. When the distractor sequence was faster than the target sequence, asynchronies were more negative at the small than at the large pitch separation. When the distractor sequence was slower than the target sequence, the opposite was the case, especially when the target pitch was higher than the distractor pitch. As mentioned earlier, a role of target pitch per se may be inferred from the results of Handel and Lawson (1983), which indicated a preference for low-pitched beats. The two-way interaction, however, remains to be explained.

An effect of pitch separation was also found in a bimanual polyrhythmic tapping task by Jagacinski, Marshburn, Klapp, and Jones (1988; see also Klapp et al., 1985, Experiment 3). Participants tapped in synchrony with tone sequences of different pitch whose IOIs exhibited a 3:2 ratio. Performance was more accurate when the pitch separation of the two sequences was small than when it was large. A small pitch separation made it possible to integrate the two sequences into a single rhythmic pattern to which the movements of the two hands could be coordinated. The present task, by contrast, required selective attention to, and synchronization with, only one of two sequences whose IOIs were in the ratio of 10:11. Although it seems that this task should be facilitated by a large pitch difference between target and distractor sequences, the results suggest only a small effect on successful trials. Indeed, synchronization with selected tones of a complex rhythm can be quite effective even in the absence of any pitch variation, as in tapping with the beat of such a rhythm (Povel & Essens, 1985; Snyder & Krumhansl, 2001). In other words, in integrated sequences, the target tones can be identified by their metrical position rather than by their pitch. Pitch may take over as a cue only when the rhythm disintegrates because of stream segregation.

In conclusion, the phase attraction effects demonstrated here presumably represent automatic processes that underlie the control of action timing, without mediation by conscious perception. Therefore, they are also less likely to be affected by variables that play a role in the perceptual organization of auditory events. However, the extent to which this is true will be apparent only after a good deal of further research has been conducted.

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