ELSEVIER

Does an auditory distractor sequence affect self-paced tapping?

Bruno H. Repp [*]

Haskins Laboratories, 300 George Street, New Haven, CT 06511-6624, USA

Abstract

This study investigated whether an auditory distractor (D) sequence affects the timing of self-paced finger tapping. To begin with, Experiment 1 replicated earlier findings by showing that, when taps are synchronized with an isochronous auditory target (T) sequence, an isochronous D sequence of different tempo and pitch systematically modulates the tap timing. The extent of the modulation depended on the relative intensity of the T and D tones, but not on their pitch distance. Experiment 2 then used a synchronization-continuation paradigm in which D sequences of different tempi were introduced only during continuation tapping. Although the D sequences rarely captured the taps completely, they did increase the tapping variability and deviations from the correct tempo. Furthermore, they eliminated the negative correlation between successive inter-tap intervals and led to intermittent phase locking when the tapping period was close to the period of the D sequence. These distractor effects occurred regardless of whether or not the taps generated auditory feedback tones. The distractor effects thus depend neither on the intention to synchronize with a T sequence nor on the simultaneous perception of two auditory sequences. Rather, they seem to reflect a basic attraction of rhythmic movement to auditory rhythms.
© 2005 Elsevier B.V. All rights reserved.

[*] Tel.: +1 203 865 6163x236; fax: +1 203 865 8963.
E-mail address: repp@haskins.yale.edu

1. Introduction

If you walk on the street and a marching band is approaching, you may find yourself involuntarily falling in step with the beat of the music. This seems like a natural thing to do, provided the tempo of the beat is not too different from your comfortable walking speed. But—you may reply—surely it is also possible to ignore the music and walk at your own pace? So it seems, but can the music really be ignored entirely? Does it perhaps still exert subtle effects on the rhythmic movement? This question, which does not seem to have been investigated previously, motivated the present study.

Involuntary coordination of action with *visually* perceived movement has been demonstrated by Schmidt and O'Brien (1997); for a recent replication, see Richardson, Marsh, and Schmidt (2005). Pairs of participants were requested to swing wrist pendulums at a preferred tempo and to maintain that tempo while looking at each other. Even though complete entrainment was generally avoided, participants showed a tendency to adopt in-phase and (to a lesser degree) anti-phase relationships more often than other phase relationships, especially when the pendulum frequencies were similar. This kind of intermittent coordination is also known as *relative coordination*.

These visual studies involved both continuous movement and a social situation that may have induced coordinative tendencies. The present study was concerned with a nonsocial laboratory task. The rhythmic movement was finger tapping (rather than walking), and the distractor was a simple sequence of identical tones (standing in for music). This simple task was adopted because it had been used in a series of previous experiments that led naturally to the situation that is of interest here. The previous studies were concerned with the effects of auditory distractors during a synchronization task. Their results are summarized below.

1.1. Phase correction

Sensorimotor synchronization is commonly studied by pacing finger taps with an isochronous target (*T*) sequence of tones. The maintenance of synchrony requires error correction (*phase correction*). Phase correction is often assumed to be based on the perception of asynchronies between taps and tones (e.g., Mates, 1994; Pressing, 1998; Repp, 2000; Vorberg & Schulze, 2002), but alternatively it may reflect phase resetting with reference to both the most recent tone and the most recent tap, either in random alternation (Hary & Moore, 1985, 1987) or simultaneously (Repp, 2001a, 2001b, 2002a). In other words, rather than being based on the temporal relation between the two events, phase adjustments may derive from each tap being timed

with reference to the separate events. The phase resetting hypothesis seems more consistent with the findings that (1) phase correction occurs in response to subliminal perturbations of sequence timing (Repp, 2000, 2001a, 2001b, 2002a) and (2) subdivision tones inserted halfway between the *T* tones not only reduce the effect of *T* tone perturbations but also elicit phase correction if they are perturbed themselves (Large, Fink, & Kelso, 2002; Repp, 2002c).

Phase correction or resetting is largely an automatic process. Not only are the participants rarely aware of correcting their timing when synchronizing with an isochronous *T* sequence, but they are also unable to suppress phase correction completely when instructed to do so. Repp (2002a) demonstrated this by phase-shifting a single event in a sequence, a perturbation that it would be advantageous to ignore. Yet, participants could not avoid reacting to it by shifting the subsequent tap in the same direction. When the perturbation was small and subliminal, participants' intention not to react to perturbations had little effect. When the perturbation was larger and detectable, the intention not to react did result in a substantial reduction of phase correction, but there was always a residual effect (see also Repp, 2002b; Repp & Keller, 2004).

1.2. The fixed-separation distractor paradigm

Repp (2003) assessed the automaticity of phase correction in a different way, by introducing irrelevant distractor (*D*) tones of different pitch during synchronization with an isochronous *T* sequence. It was expected that these tones would automatically engage phase correction when they occurred close to a *T* tone. Indeed, when a single *D* tone was placed near a *T* tone, it elicited an involuntary phase correction response (i.e., a temporal shift of the subsequent tap) that was about half as large as that elicited when the *T* tone itself was shifted to the temporal position of the *D* tone. Thus, it seemed that a *D* tone and a *T* tone engaged the phase correction mechanism simultaneously, as if the *T* tone had been shifted by half the distance between them. Interchanging the *T* and *D* tones had no effect: Shifting a *T* tone by *x* ms and placing a *D* tone in the *T* tone's original position elicited the same half-size phase correction response as placing a *D* tone *x* ms from a *T* tone. When the *D* tone was separated from the *T* tone by more than about 80 ms, however, its effect on tap timing waned.

In a second experiment, Repp (2003) presented isochronous sequences of *D* tones at various fixed temporal distances from the *T* tones. Thus, the participants heard two interleaved tone sequences, which had the same tempo but differed in pitch, and they attempted to synchronize with one sequence while ignoring the other. The temporal separation (or relative phase) of the sequences was varied across trials. Participants' taps were found to shift in the direction of the *D* tones when they were close to the *T* tones, an effect referred to by Repp as *phase attraction*. The attraction was asymmetric, being much stronger when the *D* tones preceded the *T* tones than when they followed them. The attraction decreased when the separation between the *D* and *T* tones was greater than about 80 ms and disappeared when the separation was 120–150 ms. The pitch distance between the *T* and *D* sequences seemed to play no role.

In several additional experiments using this fixed-separation distractor para-
digm, Repp (2004) varied the T sequence tempo and obtained results suggesting
that the attraction of taps to the D tones is governed by the absolute temporal sepa-
ration of the T and D sequences, not by their relative phase. The results indicated
that the D tones attract taps if the former are within 120–150 ms of the T tones,
regardless of T sequence tempo. The attraction thus seemed to be mediated by a
perceptual grouping or integration of the T and D tones within a fixed temporal
window, so that they engaged the phase correction mechanism as a perceptual unit.
This will be called the *perceptual integration hypothesis* in the following. An alterna-
tive hypothesis is that taps are attracted directly to D tones. To test that *direct
attraction hypothesis*, Repp changed the task from in-phase to anti-phase tapping.
In that case, the D tones should exert maximal attraction when they are close to the
taps but far from the T tones, and little attraction when they are close to the T tones
but far from the taps. The results, however, resembled those observed for in-phase
tapping in that attraction was strongest when the D tones were close to the T tones,
and thus supported the perceptual integration hypothesis. Only at the slower of two
T sequence tempi, an additional weaker tendency for taps to be attracted directly to
D tones was noted.

The fixed-separation distractor paradigm was also used by Repp and Penel (2004)
in a cross-modal study. Auditory distractors (tones) combined with visual targets
(lights) had much larger effects than visual distractors combined with auditory tar-
gets. Varying the loudness of the auditory stimuli had no effect in either condition.
Although the authors' conclusion that "rhythmic movement is attracted more
strongly to auditory than to visual rhythms" (the title of their article) suggests direct
attraction of taps to sounds, an interpretation of the results in terms of cross-modal
perceptual integration is by no means ruled out and would be consistent with other
demonstrations of auditory dominance in cross-modal perception of timing (Ascher-
sleben & Bertelson, 2003; Fendrich & Corballis, 2001; Morein-Zamir, Soto-Faraco,
& Kingstone, 2003; Recanzone, 2003; Repp & Penel, 2002).

1.3. The variable-separation distractor paradigm

A variable-separation distractor paradigm was employed in Experiments 3 and 4
of Repp (2003): T and D sequences having different tempi were interleaved, so that
their temporal separation (and relative phase) changed continuously within each
trial. The results obtained with this paradigm were consistent with those obtained
previously with fixed temporal separations: Overall, there was an increased tendency
of taps to precede the T tones, evidently caused by the stronger effect of leading than
of the lagging D tones, and in addition the asynchronies between taps and T tones
(and consequently the inter-tap intervals as well) exhibited a periodic modulation,
caused by the changing temporal relationship between the D and T tones. The pitch
distance between the sequences again had little effect, as long as the participants syn-
chronized with the correct sequence. (They often synchronized with the wrong
sequence when the pitch separation was small, but that may have been an attentional
problem.) Distractor effects were shown by all the participants in all conditions and

generally occurred without participants' awareness, which attests to the automaticity of the phase correction process that presumably underlies these effects.

1.4. The present study

The present experiments used the variable-separation distractor paradigm. The purpose of Experiment 1 was to replicate the earlier finding of systematic modulation of asynchronies by *D* tones and to re-examine the role of pitch separation, using an experimental design that reduced attentional confusion between the *T* and *D* sequences. In addition, the experiment investigated for the first time the effect of varying the relative intensity of the *T* and *D* tones. Although an auditory intensity manipulation had had no effect in the cross-modal study of Repp and Penel (2004), it was expected to have an effect within the auditory modality, such that distractor effects would be enhanced when the *D* tones are louder than the *T* tones, and reduced when the *D* tones are softer than the *T* tones.

Against the useful backdrop provided by the results of Experiment 1, the main experiment (Experiment 2) then investigated whether a *D* sequence affects self-paced tapping. A synchronization-continuation paradigm (Stevens, 1886; Wing & Kristofferson, 1973) was used for that purpose, and the *D* sequence was introduced only during the continuation segment. This novel distractor condition was clearly relevant to the question of whether the *D* tones can attract taps directly or only via perceptual integration with the *T* tones: Because there are no *T* tones in self-paced tapping, *D* tones should be ineffective according to the perceptual integration hypothesis. In anticipation of that possible outcome, Experiment 2 also included a condition in which each tap generated a feedback tone different in pitch from the *D* tones. This created a perceptual situation similar to that in Experiment 1, with both *T*-like tones and *D* tones being present. According to the perceptual integration hypothesis, a distractor effect might emerge in that condition via grouping of *D* tones with feedback tones. By contrast, the direct attraction hypothesis predicts clear distractor effects (i.e., modulation of inter-tap intervals and possibly even synchronization with *D* tones) in self-paced tapping, with or without feedback tones. In fact, the feedback tones might even reduce the distractor effects by providing a perceptual reference for self-paced tapping.

Another pertinent idea is that distractor effects may be contingent on the intention to synchronize taps with *T* tones. This *task relevance hypothesis* is inspired by findings of Folk and Remington (1998) and Folk, Remington, and Johnston (1992), showing that irrelevant distractors in a visual spatial cuing task do not capture attention unless they have task-relevant properties. The task relevance hypothesis predicts that *D* tones should have no effect in self-paced tapping, even when the taps produce target-like feedback tones, because there is no intention of coordinating with any tones.

In summary, then, *D* tones should interfere with self-paced tapping according to the direct attraction hypothesis, should not interfere at all according to the task relevance hypothesis, and should interfere only when feedback tones are present according to the perceptual integration hypothesis.

2. Experiment 1

The purpose of Experiment 1 was to replicate the distractor effect obtained previously with interleaved sequences of different tempi, namely a periodic modulation of asynchronies. The experiment also reassessed the effect of pitch separation, and for the first time investigated the role of the relative intensity of T and D tones. Importantly, steps were taken to prevent inadvertent synchronization with the D sequence (a methodological problem in Repp, 2003) by reducing uncertainty about characteristics of the T sequence: The T sequence had a fixed tempo and a fixed pitch that was always lower than that of the D sequence.

2.1. Methods

2.1.1. Participants

The 8 participants (including the author) were all musically trained and regular participants in synchronization experiments. Musical training ranged from professional level (2 violinists, 1 violist, 1 clarinetist) to advanced amateur level (2 active pianists) to a minimum of 6 years of instruction (1 active percussionist, 1 inactive pianist). Ages ranged from 21 to 35, except for the author who was 58 at the time.

2.1.2. Materials

Each trial consisted of two interleaved isochronous sequences of high-pitched, freely decaying digital piano tones. The T sequence always had an inter-onset interval (IOI) of 500 ms, whereas the D sequence had an IOI of either 450 or 550 ms. This resulted in two tempo conditions: $D450$ and $D550$. A trial always started with the T sequence alone. The D sequence started in phase with the 7th T tone. From that point on, the two sequences continued together for four complete joint cycles, until they ended again in phase. This resulted in 6 + 36 T tones and 40 D tones in the $D450$ condition, and 6 + 44 T tones and 40 D tones in the $D550$ condition. The pitch of the T tones was fixed at MIDI pitch 80 (G#5, about 831 Hz), whereas the D tones were either at MIDI pitch 82 (A#5, about 932 Hz) or at MIDI pitch 100 (E7, about 2637 Hz). The pitch difference thus was either 2 or 20 semitones.

In addition, the relative intensity of the T and D tones was varied by independently varying the intensity of each. Intensity was specified in terms of MIDI key depression velocity (v), which was either 30 or 60. The difference between these values represents an intensity difference of approximately 10 dB, according to earlier acoustic measurements (Repp, 1997: Fig. 1). Thus, there were four relative intensity conditions: $Tv30/Dv30$, $Tv30/Dv60$, $Tv60/Dv30$, and $Tv60/Dv60$. No difference was expected between the two equal-intensity conditions.

All in all, there were 16 different trials, resulting from the factorial combination of two D tempi, two D pitches, two T intensities, and two D intensities. Seven different randomizations (blocks) of these trials were prepared, the first of which served as practice.

2.1.3. Equipment and procedure

The sequence tones were produced on a Roland RD-250s digital piano under control of a program written in MAX 3.0. The program ran on a Macintosh Quadra 660AV computer, which was connected to the piano via a MIDI translator. [1] Participants sat in front of the computer monitor on which the current trial number was displayed and listened to the sequences over Sennheiser HD540 II earphones. They tapped on a Roland SPD-6 electronic percussion pad, and the taps were registered by the MAX program via the MIDI translator.

The participants tapped with the index finger of their preferred hand (the right hand for all but one), while their wrist and other fingers typically rested on the percussion pad. They were instructed to start tapping with the third T tone and to continue tapping in synchrony with the T tones while ignoring the D tones. In case they noticed that they had synchronized with the wrong sequence, they were to repeat the trial by clicking a "repeat" button on the computer screen. This option was used rarely, and only the data of the repeated trial were analysed.

Trials were self-paced. The participants started a block by clicking a "start" button on the screen and initiated each trial by pressing the space bar of the computer keyboard. There was a 2-s delay before the trial started. After each block, there was a short break during which the data were saved and the randomization for the next block was read in.

2.1.4. Analysis

Despite the constant pitch and tempo of the T sequence, and despite the possibility of repeating trials, some participants occasionally did not maintain synchrony, apparently without noticing it. Altogether, 22 trials (2.9%) were excluded from analysis because progressive phase drift was apparent in the asynchronies (implying synchronization with the D sequence or perhaps with neither sequence). Sixteen of these trials, contributed by several participants, occurred when the pitch separation between the T and D sequences was small. The other six trials, all contributed by the musically least experienced participant, surprisingly occurred when the pitch separation was large. An additional 6 trials (0.8%) were inadvertently skipped, presumably due to bounce of the space bar of the computer keyboard. In no case did the exclusion of trials prevent the calculation of trial averages.

The asynchronies between taps and T tones were computed (a negative asynchrony means that the tap leads the tone) and averaged first across the repetitions of each trial type, then across participants, and finally across some conditions if required for graphic display. For statistical analyses, the standard deviation of the asynchronies was computed within each trial, not including the taps made before the D sequence started. These standard deviations were averaged across trial repetitions

---

[1] Due to a peculiarity of this setup, the tempo of the output was about 2.4% faster than specified in the MIDI instructions, as determined in earlier acoustic waveform measurements. The participants' key presses were registered at a correspondingly slower rate. All millisecond values are reported as they appeared in the MAX environment. (This note does not apply to Experiment 2, where newer equipment was used.) MAX software is now supported by http://www.cycling74.com/.
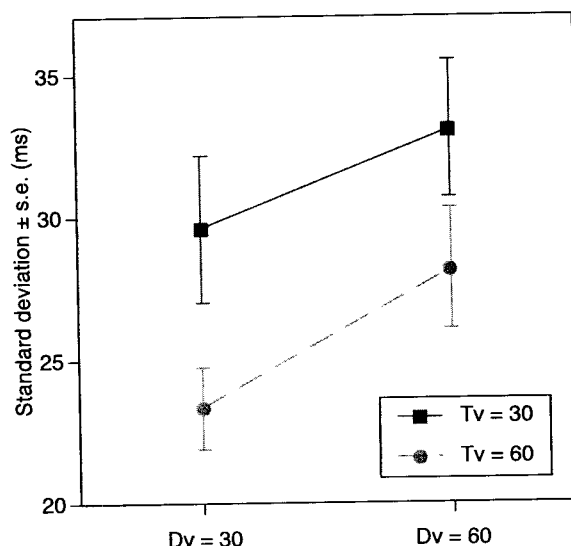
Fig. 1. Mean standard deviations (with standard error bars) for the combinations of two target intensities (Tv) and two distractor intensities (Dv), specified in terms of MIDI velocity.

and then were subjected to a $2 \times 2 \times 2 \times 2$ repeated-measures ANOVA with the variables of D tempo, D pitch, T intensity, and D intensity.

2.2. Results

Fig. 1 shows the within-trial variability of asynchronies as a function of T and D intensities. As predicted, variability was lowest when the T tones were louder than the D tones, highest when the T tones were softer than the D tones, and intermediate in the two equal-intensity conditions. The main effects of T intensity $F(1,7) = 57.6$, $p < .0001$, and of D intensity, $F(1,7) = 83.1$, $p < .0001$, were both significant, whereas the interaction was not. No other effects in the ANOVA were even close to significance. In particular, there was no effect of D tempo or of D pitch on the variability of asynchronies.

Fig. 2 shows the mean asynchronies across T sequence positions for the four combinations of T and D intensities, separately for the two D tempo conditions ($D450$, $D550$). The expected periodic modulation of the asynchronies can be seen clearly in each condition. Within each panel, the effect of D and T intensities on the extent of the modulation can be seen. Furthermore, it is evident that the distractors made the asynchronies more negative overall, compared to the initial asynchronies before the D sequence had started. The points at which the D and T sequences were in phase are indicated by zeroes on the abscissa. With the faster D sequence ($D450$), the asynchronies were least negative at the in-phase points, whereas with the slower D sequence ($D550$) they were most negative. Moreover, reading the graphs from left to right, the asynchronies moved away from the in-phase points (becoming more negative with
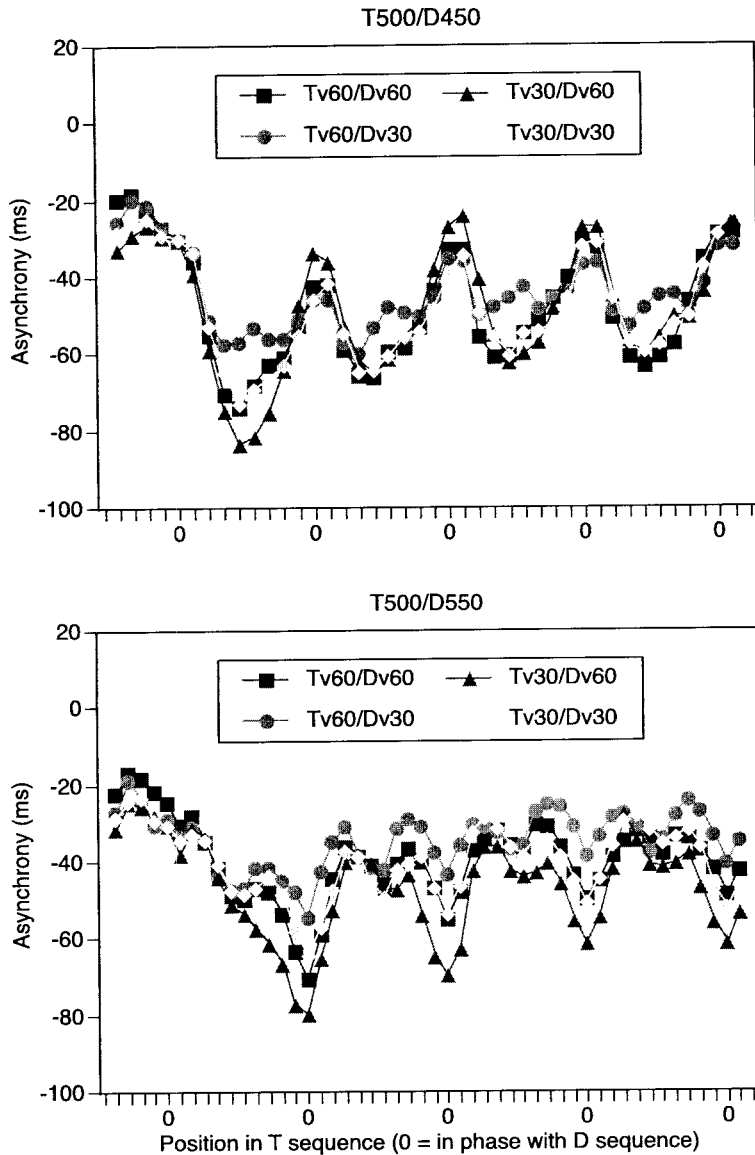
Fig. 2. Mean asynchronies across target sequence positions in the two distractor tempo conditions (*D*450 and *D*550) for the four combinations of target intensities (*Tv*) and distractor intensities (*Dv*), specified in terms of MIDI velocity.

*D*450, less negative with *D*550) more quickly than they moved toward them, which resulted in asymmetric shapes of the modulation cycles. These asymmetries can be explained by appealing to the previously observed stronger attraction of taps to leading than to lagging distractors (see also Repp, 2003): As a trial progressed, the *D*450

tones overtook the T tones and thus pulled the taps away from the T tones; then the pull lost its force, and the taps returned gradually toward the T tones. By contrast, the D550 tones pushed the taps gradually toward the T tones as the T tones were about to overtake the D tones; when the in-phase point was reached, the taps returned rapidly to their typical negative asynchrony (i.e., they moved away from the T tones), aided by the weak attraction to lagging distractors. These descriptions hold regardless of whether the distractor effects reflect perceptual integration or direct attraction.

Finally, it should be noted that the modulation of asynchronies shown in Fig. 2 implies a similar modulation of ITIs, albeit with different inflection points. (This is so because the time series of ITIs constitutes the first difference of the time series of asynchronies plus a constant, and the first difference or derivative of a sine-like function is a cosine-like function.) In Experiment 2, analysis was focused on ITIs because there was no T sequence relative to which asynchronies could be computed.

2.3. Discussion

The results of Experiment 1 replicate the findings of Repp (2003, 2004) by showing that the D tones exert an apparently unavoidable modulatory effect on the timing of taps that are intended to be synchronized with a T sequence. The results also replicate the earlier finding that the overall magnitude of the modulation is similar for D sequences that are faster or slower (by the same absolute IOI difference) than a fixed-tempo T sequence. Furthermore, although Repp (2003) had found a small effect of pitch separation in one of two experiments, that effect was absent here. In the earlier experiment, many trials had to be discarded because participants often synchronized unintentionally with the D sequence when the pitch separation was small. Although the T sequence always started before the D sequence in that study, the confusion was clearly caused by the fact that the tempo and pitch of the T sequences and D sequences changed from trial to trial, so that the values assigned to the T sequence in one trial could be assigned to the D sequence in the next trial. The present experiment minimized such confusions by keeping the tempo and pitch of the T sequence constant. Thus, the lack of an effect of pitch separation on the magnitude of the distractor effect seems to be real, suggesting that the underlying phase correction process is sensitive solely to the times of occurrence of auditory events, not to their spectral properties. This finding, incidentally, is somewhat difficult to reconcile with the perceptual integration hypothesis, for one might surmise that two tones that are widely separated in pitch would be more difficult to group together than two similar tones.

A novel—although hardly surprising—finding of Experiment 1 is that the relative intensity of the T and D tones makes a difference: The louder the D tones are relative to the T tones, the larger is the modulation of the asynchronies. This contrasts with the finding of Repp and Penel (2004) that the relative loudness of tones, be they targets or distractors, is unimportant when they are in competition with visual stimuli. In the cross-modal distractor paradigm, the modality difference evidently overrides any differences in the relative salience of stimuli. Within the auditory modality,

however, relative salience is clearly important. Moreover, the effect of relative intensity was equally large at small and large pitch separations.

Experiment 1 was not designed to investigate specifically whether the distractor effects arise from direct attraction of taps to D tones or whether the effects are mediated by perceptual integration of the T and D tones. Experiment 2, however, addressed this issue head-on.

3. Experiment 2

The purpose of Experiment 2 was to examine whether D tones affect the timing of the self-paced taps. A synchronization-continuation paradigm was used for that purpose: Participants first synchronized with a T sequence and then continued tapping at the same tempo. After a brief period of self-paced tapping, a D sequence started and continued for a while. After the D sequence had ended, participants continued their self-paced tapping for another brief period, so that any aftereffects of the D sequence could be assessed. The experiment comprised two conditions which constituted separate sessions: In the no-feedback (NFB) condition participants merely heard the thuds of their taps on the percussion pad, whereas in the feedback (FB) condition each tap generated a tone identical to the T tones that had been present during the initial synchronization segment. During the distractor segment of trials, this resulted in a perceptual situation very similar to that in Experiment 1, with both T-like tones and D tones being present.

If taps are attracted to D tones directly, distractor effects in self-paced tapping should be similar to, and probably larger than, those observed in synchronized tapping. Not only should the ITIs be modulated by the D tones, but also more extreme distractor effects might occur in the form of phase locking and period entrainment, because there are no T tones providing a stable reference. By contrast, if distractor effects are mediated by perceptual integration of D and T tones and/or by the intention to synchronize, distractor effects in self-paced tapping should be minimal, especially in the NFB condition. In the FB condition, perceptual integration of self-produced T-like tones with D tones might lead to distractor effects, however.

3.1. Methods

3.1.1. Participants

Six of the 8 participants were the same as in Experiment 1. The two new participants had qualifications similar to those of the earlier participants they replaced, and they even played the same instruments (percussion, piano).

3.1.2. Materials

Each trial started with a sequence of 10 isochronous T tones having a MIDI pitch of 100 (E7, about 2637 Hz). The T-IOI was either 400 ms (fast T tempo) or 600 ms (slow T tempo). Following the onset of the last T tone, there was a long interval of 4000 or 6000 ms, respectively, before the onset of the first D tone, if any. D tones had

a MIDI pitch of 97 (C#7, about 2217 Hz) and thus were three semitones lower than T tones. The D sequence was isochronous and consisted of 20 tones with D-IOIs of 360, 380, 400, 420, or 440 ms for a T-IOI of 400 ms, and D-IOIs of 540, 570, 600, 630, or 660 ms for a T-IOI of 600 ms (i.e., −10%, −5%, 0, +5%, or +10% of each T-IOI). Following the onset of the last D tone, there was another long interval of 4000 or 6000 ms, respectively, until a final tone with a MIDI pitch of 95 (B6, about 1976 Hz) sounded, which was the signal to stop tapping. T and D tones had the same nominal intensity (MIDI velocity of 60). Each trial thus consisted of four segments: (1) synchronization (*Synch*; 8 taps); (2) pre-D continuation (*Cont 1*; about 10 taps); (3) D continuation (*Dist*; about 18–22 taps); (4) post-D continuation (*Cont 2*; about 10 taps). In the FB condition, each tap made after cessation of the initial T sequence produced a tone identical to a T tone. There were also baseline (no-D) trials without a D sequence, in which case the Dist segment lasted as long as it would have lasted if a D sequence with a D-IOI of 400 or 600 ms had been present.

Five D tempi and one no-D trial for each T tempo resulted in 12 trial types that were presented in 10 different randomizations (blocks) in each condition (NBF and FB). The NFB and FB conditions constituted two separate sessions, usually one week apart. An additional practice block was presented at the beginning of the first (NFB) session.

3.1.3. Equipment and procedure

Equipment and procedure were similar to those in Experiment 1, except for the following differences: Presentation of sequences and recording of taps was controlled by MAX 4.0.9 software running on an iMac G4 computer. Participants were instructed to continue tapping at the same tempo after the end of the T sequence, to ignore the D sequence, and to continue tapping after the end of the D sequence until a single tone sounded. In the FB condition, they were informed that, after the end of the T sequence, their taps would produce tones sounding like the T tones.

3.2. Results and discussion

3.2.1. Inter-tap intervals

The first data analysis examined the mean ITIs across the four segments of the trials, to see whether the participants had been able to maintain the initial tempo (Synch) during continuation tapping (Cont 1), whether a D sequence (regardless of tempo) had any effect on the mean ITI during the third (Dist) segment, and whether that effect carried over into the fourth (Cont 2) segment. The relevant results are shown in Fig. 3.

It can be seen that, at both T tempi, participants tapped slightly faster during the Cont 1 segment than during the initial Synch segment and sped up even more during the Dist and Cont 2 segments. At the faster T tempo (T400), the presence vs. absence of a D sequence had no effect on the mean ITI. At the slower T tempo (T600), however, the presence of a D sequence led to a more pronounced shortening of the ITIs
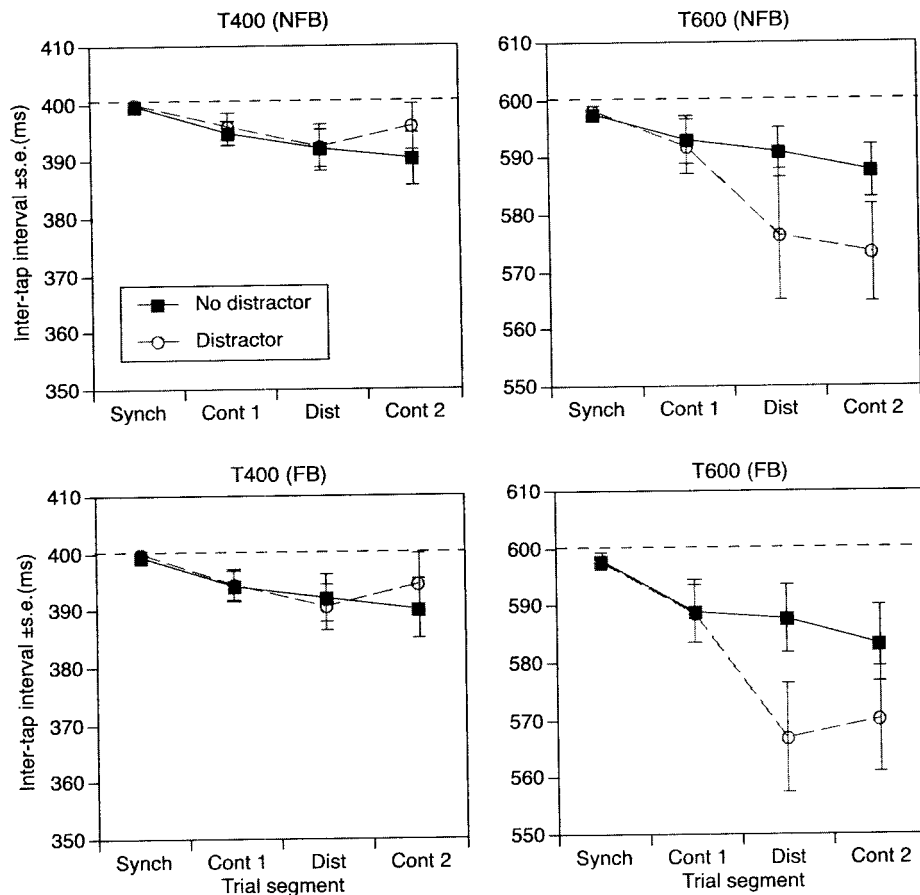
Fig. 3. Mean inter-tap intervals (ITIs) in the four conditions defined by target sequence tempo (T400, T600) and absence vs. presence of feedback (NFB, FB). Each panel compares the mean ITIs of trials without distractors with those of trials with distractors (averaged across the five distractor tempi). Mean ITIs are shown for each of the four segments of trials with distractors (Synch, Cont 1, Dist, Cont 2) and for analogous segments of trials without distractors.

during both the Dist and Cont 2 segments. This occurred regardless of whether or not the taps produced a feedback tone.

A $2 \times 2 \times 2 \times 4$ repeated-measures ANOVA with the variables of T-tempo (T400 vs. T600), feedback (NFB vs. FB), distractor (present vs. absent), and segment (Synch, Cont 1, Dist, Cont 2) confirmed these observations: The T-tempo × Distractor × Segment interaction was significant, $F(3,21) = 12.28$, $p < .007$, $\varepsilon = .39$ (Greenhouse–Geisser epsilon), and all the component main effects and two-way interactions of the triple interaction were significant as well. No effect involving feedback was significant.

The next analysis examined the specific effect of D sequence tempo on the mean ITI during the Dist and Cont 2 segments. If phase locking and period entrainment

occurred, then the mean ITI should match, or at least increase monotonically with, the IOI of the D sequence. Fig. 4 shows the relevant data for the Dist segment. The data for the Cont 2 segment are not shown but were very similar.

There was little evidence for a monotonic positive relationship between D-tempo and mean ITI. However, a $2 \times 2 \times 5 \times 2$ repeated-measures ANOVA with the variables of T-tempo, feedback, D-tempo (D-IOI expressed as a percentage of T-IOI), and segment (Dist, Cont 2) did reveal a significant main effect of D-tempo, $F(4,28) = 4.68, p < .03, \varepsilon = .53$. Decomposition of that effect into polynomial contrasts (performed automatically by Systat, the statistics program used) showed that only the quadratic component was significant, $F(1,7) = 9.50, p < .02$, due to an upward-convex relationship between D-IOI and mean ITI. In addition, the D-tempo × Feedback interaction reached significance, $F(4,28) = 5.69, p < .02, \varepsilon = .50$. In
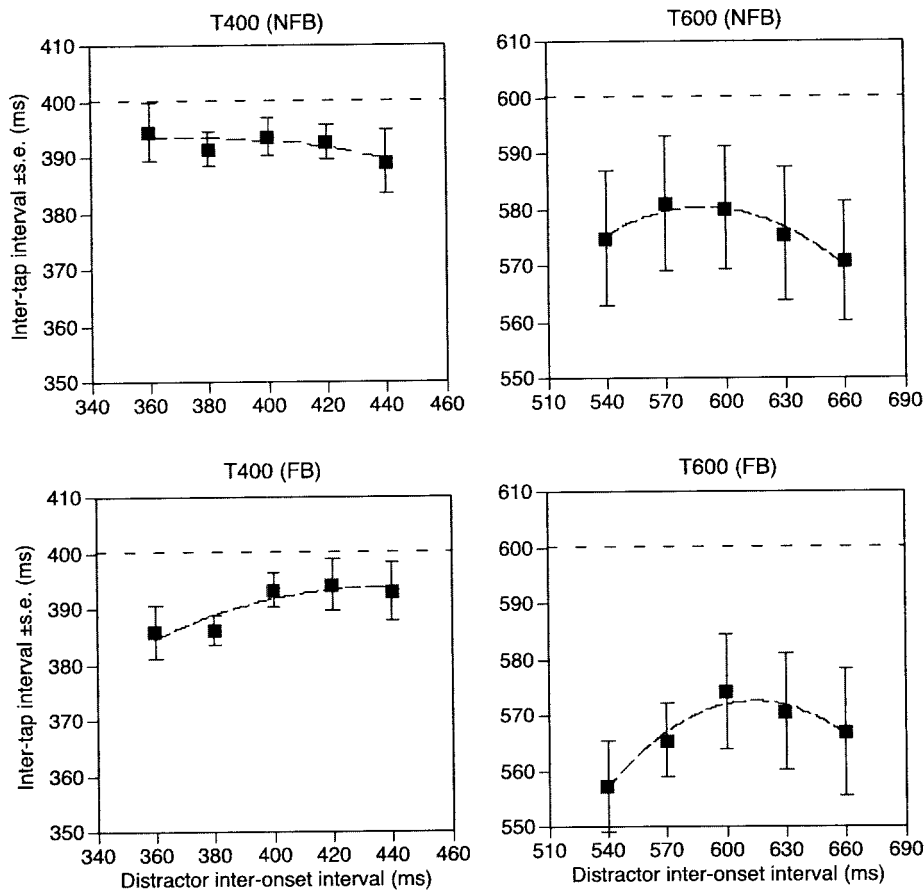

Fig. 4. Mean inter-tap intervals (ITIs) during the distractor segments of trials in the four conditions defined by target sequence tempo (T400, T600) and absence vs. presence of feedback (NFB, FB). Each panel shows the mean ITI as a function of distractor inter-onset interval (IOI). The dashed curves represent quadratic fits to the data points.

that case, only the linear component of the effect was significant, $F(1,7) = 11.00$, $p < .02$, implying a relative tilting of the upward-convex function as a function of feedback. There was no significant effect involving segment or T-tempo, except for the main effect of T-tempo, which was trivially significant.

These results are difficult to interpret. It is evident, however, that the tapping tempi neither matched nor were monotonically related to the D-tempi. Clearly, the phase and period of the taps were not entrained to those of the D sequence, at least not in the majority of trials. If there were any distractor effects, they must have been of a more subtle nature, such as a gentle modulation of the ITIs.

3.2.2. Variability

The next two analyses examined the standard deviations of the ITIs. If the ITIs were modulated by the D tones, they should show an increase in variability during the Dist segment. The relevant results are shown in Fig. 5.

Fig. 5 shows the general effect of any D sequence on the variability of ITIs, regardless of the D-tempo. It can be seen that the presence of D tones indeed increased the variability of ITIs during the Dist segment, especially at the slower T-tempo ($T600$), relative to the no-D baseline. The increase almost disappeared in the following continuation segment (Cont 2). [2] In addition, it can be seen that variability was higher during synchronization (Synch) than during subsequent continuation tapping (Cont 1), particularly at the slower T-tempo, which may reflect additional variance generated by phase correction during synchronization (cf. Semjen, Schulze, & Vorberg, 2000) but could also be due to an initial "tuning in" during the Synch segment. In the absence of a D sequence, variability increased somewhat during the remainder of a trial. Obviously, variability was also greater at the slow than at the fast tapping tempo. The feedback tones made little difference.

The ANOVA on these data (analogous to that on the ITI data in Fig. 3) revealed a significant T-tempo × Distractor × Segment interaction, $F(3,21) = 9.76$, $p < .001$, $\varepsilon = .87$, just as for the ITIs. All the component main effects and two-way interactions of the triple interaction were also significant, except for the T-tempo × Distractor interaction, which fell just short of significance. The main effect of feedback also fell short of significance, but the T-tempo × Feedback interaction was significant, $F(1,7) = 19.37$, $p < .003$. It reflects a reduction of variability in the $T600$ condition when feedback tones were present (FB).

Fig. 6 shows the specific effects of D-tempo on the variability of ITIs during the distractor (Dist) and subsequent continuation (Cont 2) segments of trials. Variability was naturally larger at the slow than at the fast T-tempo, $F(1,7) = 63.01, p < .001$, and it also was larger when distractors were present (Dist) than when they were absent

---

[2] Using a spreadsheet program, the standard deviations of ITIs were calculated within each segment, with the segments being delimited by the nominal starting and ending times of the D sequence, assuming that participants tapped at the nominal tempo. If a participant tended to tap faster, some taps that properly still belonged to the Dist segment were included in the Cont 2 segment. This may account for the small carry-over of the increase in variability. (This note does not apply to the later analyses implemented in MATLAB, which determined the limits of the Dist segment precisely for each trial.)
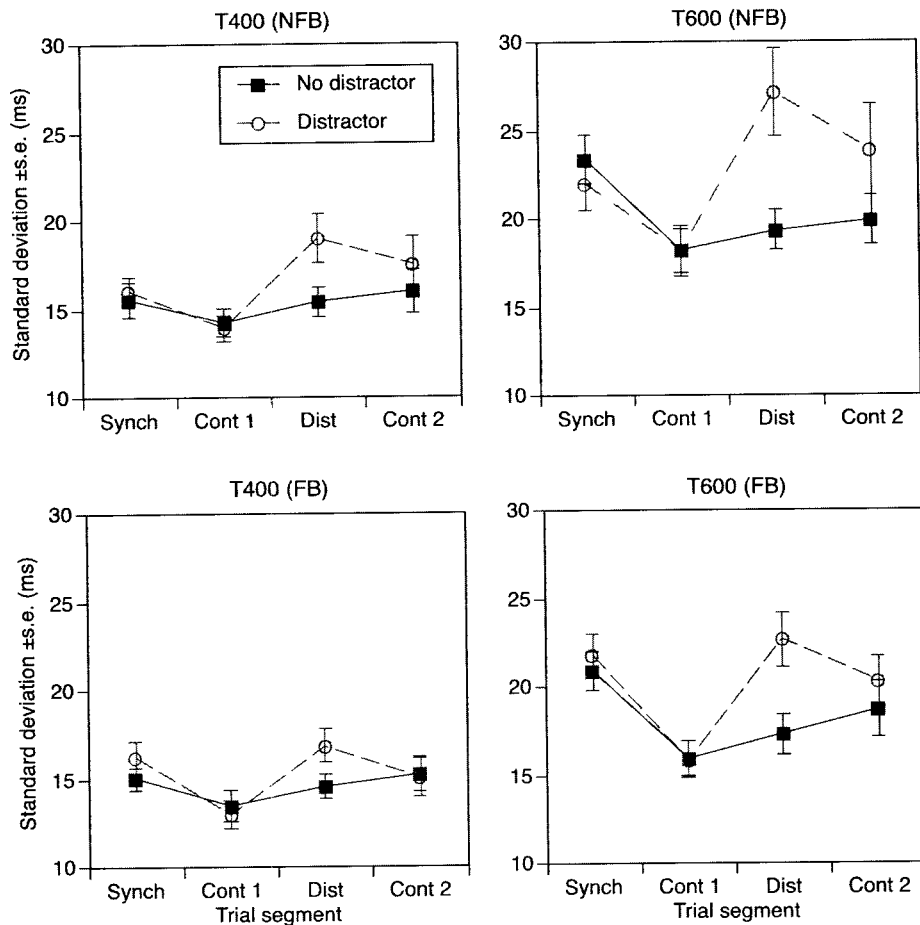
Fig. 5. Mean within-segment standard deviations (SDs) of ITIs in the four conditions defined by target sequence tempo (*T*400, *T*600) and absence vs. presence of feedback (NFB, FB). Each panel compares the mean SDs in trials without distractors with those in trials with distractors (averaged across the five distractor tempi). Mean SDs are shown for each of the four segments of trials with distractors (Synch, Cont 1, Dist, Cont 2) and for analogous segments of trials without distractors.

(Cont 2), $F(1,7) = 16.93$, $p < .004$. The apparently lower variability in the FB than in the NFB condition did not reach significance here. The ANOVA further revealed a significant main effect of *D*-tempo, $F(4,28) = 3.90$, $p < .04$, $\varepsilon = .60$, although none of the orthogonal polynomial contrasts of the effect reached significance. The data suggest that variability was slightly lower when the *D*-tempo matched the nominal tapping tempo. Furthermore, the Feedback × *D*-tempo interaction was significant, $F(4,28) = 4.02$, $p < .03$, $\varepsilon = .61$, mainly because of its cubic component, $F(1,7) = 13.77$, $p < .008$, which indicates a more curvilinear relationship between *D*-tempo and variability when feedback tones were present (FB) than when they were absent (NFB). However, there was no significant interaction involving segment.
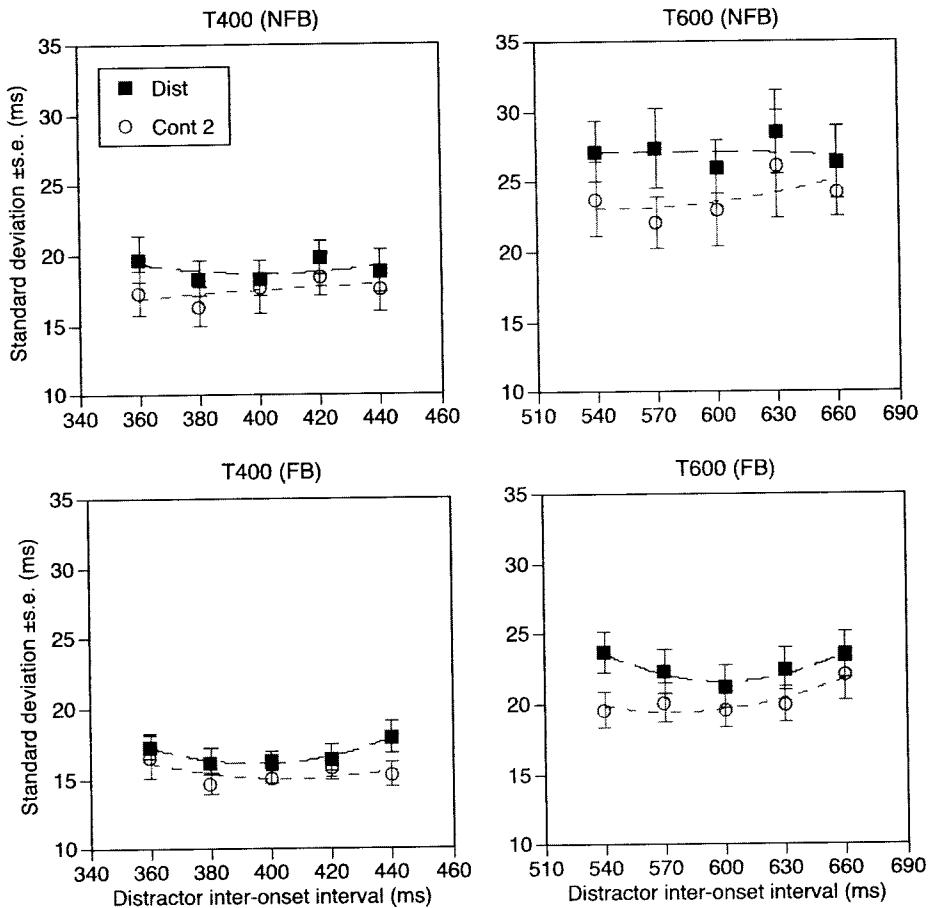
Fig. 6. Mean within-segment standard deviations (SDs) of ITIs during the distractor segments of trials in the four conditions defined by target sequence tempo (T400, T600) and absence vs. presence of feedback (NFB, FB). Each panel shows the mean SDs as a function of distractor inter-onset interval (IOI) for the distractor (Dist) and subsequent continuation (Cont 2) segments of trials. The dashed curves represent quadratic fits to the data points.

Three further analyses, implemented in MATLAB, attempted to find evidence for modulation of the ITIs by the D sequence during the Dist segment. In Experiment 1, asynchronies could be measured and simply averaged across repeated trials of T-tempo/D-tempo combinations, but in Experiment 2 that was not possible, not only because there was no T sequence during the Dist segment but also because the D sequence started essentially in random phase with respect to the taps, as a consequence of phase drift of the taps during the Cont 1 segment. Therefore, different approaches had to be taken which treated each trial individually. The first analysis, an attempt to look for a positive relationship between the first difference of ITIs (i.e., acceleration) and the temporal separation between taps and D tones, yielded puzzling

results and therefore is not reported. The other two analyses, however, led to interesting and interpretable outcomes.

3.2.3. Autocorrelations

The periodic modulation of the ITIs during the Dist segment could have two effects on the autocorrelation function: First, modulation may be reflected in positive autocorrelations at long lags corresponding to the joint cycle duration (i.e., the time between successive in-phase points) of the taps and the D sequence. Second, systematic modulation of ITIs may introduce a positive dependency between successive ITIs that reduces the negative lag-1 autocorrelation that is typically observed in self-paced tapping (Wing & Kristofferson, 1973).

After extracting from each trial the ITIs belonging to the Dist segment, autocorrelations were computed up to lag 10. The correlations were averaged across repetitions of the same trial type and then across participants, and their 95% confidence interval was computed. Because there were only 18–22 taps during the Dist segment, autocorrelations at lags larger than 10 were considered too unreliable to be computed and interpreted. This meant, however, that there was little hope of detecting any periodic modulation caused by D sequences whose IOIs were related to the T-IOIs by ratios of 20:19, 1:1, and 20:21 (the middle three D-tempo conditions). Only the extreme D-sequence tempi, whose IOIs represented ratios of 10:9 and 10:11 with the T-IOI could possibly have caused positive autocorrelations at lags close to 10. In fact, however, all mean autocorrelations at lags 2–10 were small and predominantly negative. Out of 9 (lags) × 2 (T-tempi) × 6 (D-tempi + no-D) × 2 (feedback) = 216 mean correlations, 62 (28.7%) were significant at $p < .05$, all of them negative; the largest mean value was $-.11$. This suggests that any slow modulation of ITIs was nonperiodic.

The prediction of a reduced lag-1 autocorrelation was confirmed, however. These data are shown in Fig. 7. Whereas a significant mean negative lag-1 autocorrelation was obtained in the absence of a D sequence (i.e., during a no-D trial segment analogous to the Dist segment in $T400/D400$ or $T600/D600$ trials), the mean lag-1 autocorrelation was generally close to zero when a D sequence was present. It was significantly negative in only two out of the twenty D conditions shown in the figure. The disappearance of the negative lag-1 autocorrelation when a D sequence is present suggests that a positive lag-1 dependency overlaid and neutralized the negative one. Such a dependency could reflect a modulation of ITIs by the D tones, but it could also be due to increased linear tempo drift in the presence of a D sequence (see Collier & Ogden, 2004).

A 2 × 2 × 2 × 2 repeated-measures ANOVA was conducted on the lag-1 and lag-2 autocorrelations only, after averaging them across D-tempi. The variables were feedback, T-tempo, distractor (present vs. absent), and lag (1 vs. 2). The Distractor × Lag interaction was significant, $F(1,7) = 9.17$, $p < .02$, reflecting the fact that the D sequence had a larger effect on lag-1 than on lag-2 correlations. The main effects of distractor, $F(1,7) = 28.71$, $p < .001$, and of lag, $F(1,7) = 15.85$, $p < .005$, were also significant, as was the main effect of T-tempo, $F(1,7) = 18.73$, $p < .003$, due to more negative correlations at the fast than at the slow T-tempo (see Fig. 7). A separate 2 × 2 × 2

ANOVA on the lag-1 correlations alone showed a significant main effect of distractor, $F(1,7) = 21.58$, $p < .002$, whereas the main effect of T-tempo fell just short of significance, $F(1,7) = 5.50$, $p < .06$. Surprisingly, there was also a highly reliable main effect of feedback, $F(1,7) = 29.81$, $p < .001$, although the effect was very small in size: The lag-1 autocorrelations tended to be more negative in the FB than in the NFB condition. A separate $2 \times 2 \times 2$ ANOVA of the lag-2 autocorrelations yielded only a main effect of distractor, $F(1,7) = 9.55$, $p < .02$: The correlations tended to be negative when there was no D sequence but positive when a D sequence was present, although all correlations were quite small.
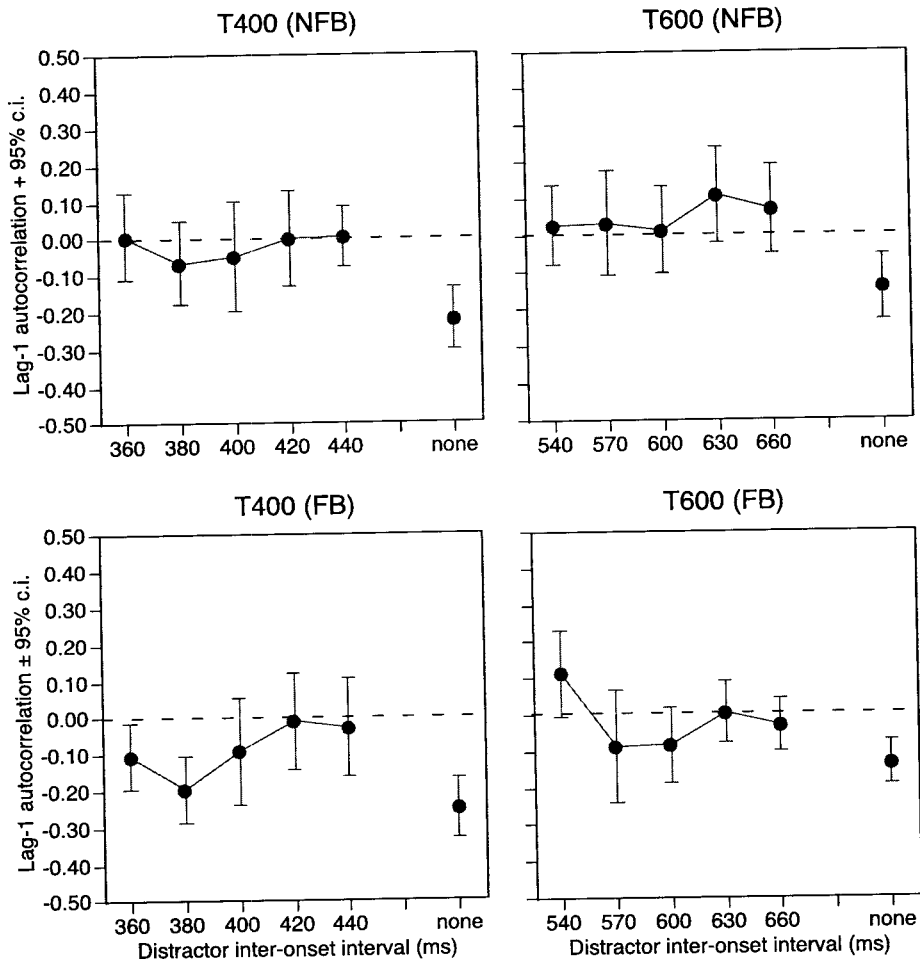

Fig. 7. Mean lag-1 autocorrelations with 95% confidence intervals as a function of distractor tempo and for the no-distractor condition in the four conditions defined by target sequence tempo ($T400$, $T600$) and absence vs. presence of feedback (NFB, FB).

3.2.4. Distribution of asynchronies

Finally, an analysis of the distribution of the asynchronies (or, equivalently here, relative phases) between taps and *D* tones was conducted. If tapping was not influenced by *D* tones, continuous phase drift (phase wrapping) should have been the result, unless the mean ITI and the *D*-IOI happened to be exactly the same. Given that the *D* sequence started essentially at a random phase relative to the taps, a flat frequency distribution of asynchronies across all trials would indicate that the *D* sequence had no effect on tapping. A peaked distribution, on the other hand, would indicate intermittent maintenance of a preferred phase relationship or asynchrony.

Frequency distributions thus were obtained for the asynchronies of all repetitions of the same trial type, both with and without feedback. However, because distributions for the NFB and FB conditions looked highly similar, these data were combined for each trial type. A distribution of virtual asynchronies was obtained for no-*D* trials by assuming a virtual *D* sequence at each of the five *D*-tempi for each *T*-tempo. The frequency distributions of the virtual asynchronies were certainly expected to be flat. To calculate the frequency distributions, the asynchronies were sorted into 20-ms bins for *T*400 trials and into 30-ms bins for *T*600 trials. In each case, the bins covered the range from $-D$-IOI/2 to D-IOI/2. The results are shown in Fig. 8. The vertical dotted line in each graph indicates zero (i.e., an in-phase relationship between taps and *D* tones), whereas the edges of the graph represent an anti-phase relationship. Negative values of asynchronies mean that the *D* tone preceded the tap, whereas positive values signify that the *D* tone followed the tap. (Note that this definition here is the opposite of the common definition of asynchronies between taps and *T*-tones.)

The results were qualitatively similar for the *T*400 and *T*600 conditions. A pronounced peak, centered on zero but tilted somewhat to the right, can be seen in the center graphs for the *T*400/*D*400 and *T*600/*D*600 conditions (heavy lines). In the conditions plotted immediately above (*T*400/*D*380 and *T*600/*D*380), a somewhat lower peak is evident on the negative side. In the top panels (*T*400/*D*360 and *T*600/*D*540), an even lower peak can be discerned at even more negative values. In the conditions plotted immediately below the center panels (*T*400/420 and *T*600/*D*630), a low peak appears on the positive side. In the bottom panels (*T*400/*D*440 and *T*600/*D*660), there is a mere hint of a hump at even more positive values. What these data reveal, then, is an intermittent preference for a particular temporal or phase relationship between taps and *D* tones. When the *D* sequence had approximately the same tempo as the taps (it will be recalled that participants tapped a little faster than the nominal *T*-tempo), the preference was for an in-phase relationship; when the *D* sequence was faster than the taps, the preference was for a relationship in which the taps lagged behind the *D* tones; and when the *D* sequence was slower than the taps, the preference was for a relationship in which the taps led the *D* tones. The larger the difference between the ITIs and the *D*-IOIs, the less pronounced was the preference and the more it deviated from the in-phase relationship. The preferences must have been intermittent because there are substantial frequency counts in all bins in all
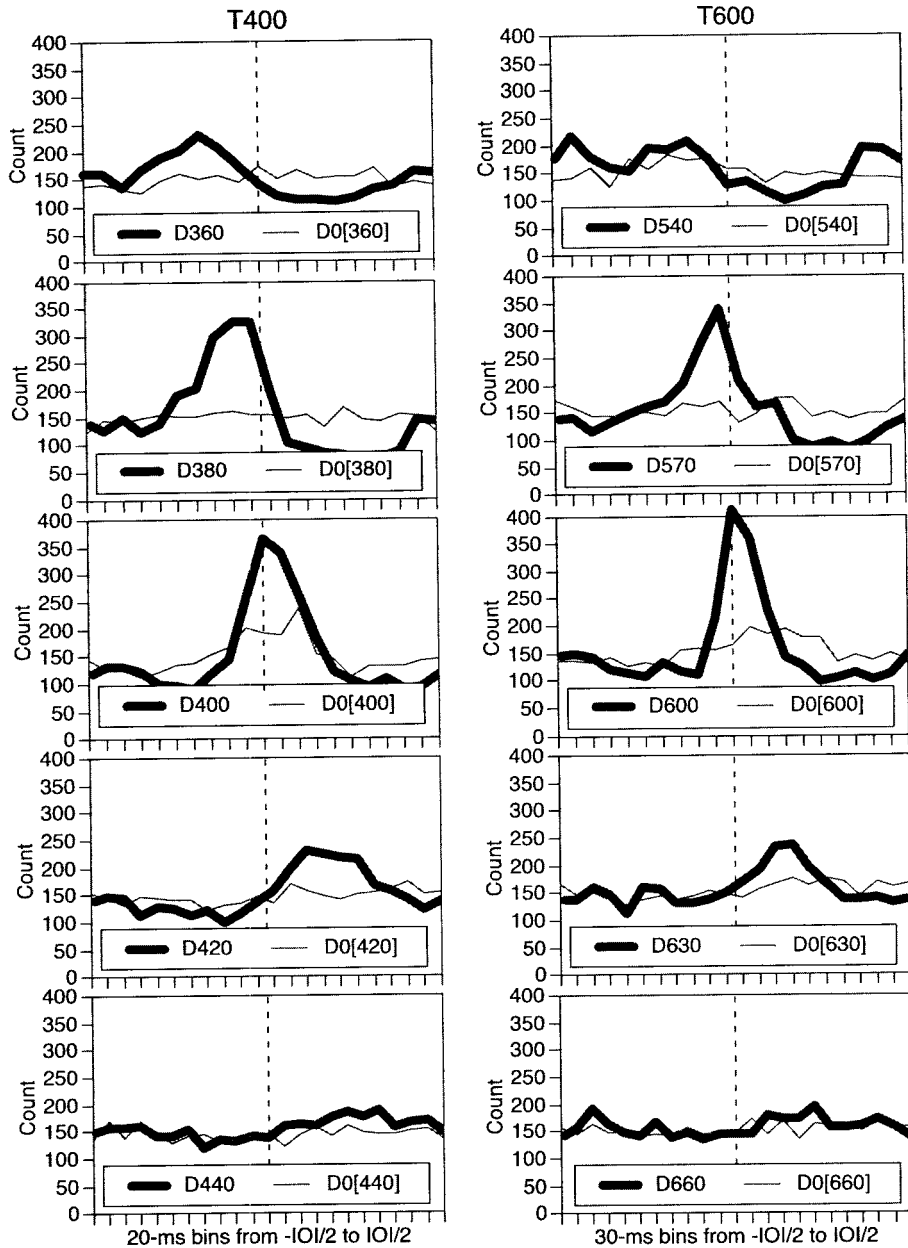
Fig. 8. Frequency histograms of the temporal separations between taps and distractor tones in the various combinations of target (T400, T600) and distractor tempi. Distractor IOIs in brackets signify the condition without a distractor sequence, where a virtual distractor sequence was assumed. The dotted vertical line indicates zero (in phase), whereas the edges of each graph correspond to −IOI/2 and IOI/2 (antiphase). The same data point is plotted on both edges of each graph.

conditions, suggesting that phase wrapping was quite common. This was confirmed by informal inspection of individual trials.

The peaks in the frequency distributions derived from trials with D sequences (heavy lines) project clearly above the distributions derived from no-D trials (thin lines), except in the extreme D-tempo conditions. The distributions for no-D trials were generally flat, except in the center panels, where a broad hump centered at a small positive value can be seen. That hump presumably indicates that the taps had not yet drifted into a completely random phase by the end of the Cont 1 segment. Thus, the virtual D sequence was more likely to have a small than a large temporal separation from the taps initially, but the distribution presumably got increasingly broad during the virtual Dist segment.

All the 8 participants showed similar patterns of frequency distributions, and no further inferential statistics were conducted on these data.

4. General discussion

This study comprised two experiments, the first of which served to demonstrate the effects a D sequence has on tapping when the task is to synchronize with a T sequence. Replicating earlier results (Repp, 2003), Experiment 1 demonstrated systematic modulations of asynchronies (and consequently also of ITIs) by a D sequence whose IOIs were either 10% shorter or 10% longer than those of the T sequence. The experiment also showed that the extent of the modulation depends on the relative intensity of the T and D tones, whereas the pitch distance between the T and D tones (2 vs. 20 semitones) is immaterial.

Experiment 2 was of central interest here because it investigated the hitherto not studied situation of self-paced tapping in the presence of a D sequence. The experiment specifically addressed the question of whether taps are attracted directly towards D tones, or whether D tones have their effect only via integration with T tones. A situation resembling that of Experiment 1 was created by making the taps produce auditory feedback tones that sounded just like T tones. If perceptual integration is a prerequisite for distractor effects to occur, the FB condition should have facilitated such effects, whereas D tones should have been easy to ignore in the NFB condition. However, if the intention to synchronize is also a prerequisite, then distractor effects should have been minimal in both feedback conditions. Finally, if taps are attracted directly to D tones, distractor effects should have occurred in both feedback conditions, possibly even to a greater extent in the NFB than in the FB condition.

What did Experiment 2 show? Let us focus first on the extreme D-tempo conditions, in which the IOIs of the D sequence were 10% shorter or 10% longer than the nominal target ITIs. These conditions are most comparable to those in Experiment 1. These D sequences increased the variability of the ITIs, but there was no evidence of entrainment of ITIs to the distractor IOIs. The D sequences virtually eliminated the negative lag-1 autocorrelation of the ITIs, which suggest that they introduced some positive dependency between successive ITIs, but the asynchrony frequency distribution

analysis showed only marginal distractor effects, if any, in these conditions. Moreover, the presence of feedback tones made little difference. On the whole, these data suggest that participants were able to ignore the *D* sequences quite well when their tempo differed sufficiently from the tapping tempo. The effects that *D* tones did have (increased variability, acceleration of tempo, reduction of lag-1 autocorrelation) did not necessarily reflect the specific temporal relationship between taps and *D* tones; if they did, the present analyses were not sensitive enough to reveal it. Therefore, these results seem more consistent with the task relevance and perceptual integration hypotheses than with the hypothesis that taps are attracted directly to *D* tones.

The other conditions, however, in which the *D*-IOIs differed from the *T*-IOI by only 5% or 0% and thus were similar to the mean ITI, yielded some evidence of direct attraction to *D* tones. This evidence comes from the asynchrony frequency distribution analysis described last. The closer the *D*-IOIs were to the ITIs, the more strongly the taps were pulled into the orbit of the *D* sequence. This pull, however, was only intermittent, and complete entrainment was rare. The ITIs generally remained different from the *D*-IOIs, and although intermittent phase locking implies a temporary similarity of ITIs and *D*-IOIs, a difference was generally regained after such episodes (unless they occurred at the end of the Dist segment). Most interestingly, the intermittent phase locking reflected a preferred in-phase relationship only when there was a close match between the mean ITI and the *D*-IOI. When the *D* sequence was faster than the taps, participants intermittently adopted a phase locking in which they lagged behind the *D* tones, thereby ensuring that they would soon be able to pull away and tap yet slower again. The opposite happened when the *D* sequence was slower than the taps. The effects were less pronounced in the latter case, probably because participants generally tapped somewhat faster than designated by the initial *T* sequence, so that the difference between the ITIs and the longer *D*-IOIs was larger than the nominal difference between *T*-IOI and *D*-IOIs. Although it could also be that a fast *D* sequence exerts a stronger effect than a slow one, previous experiments addressing that issue (the present Experiment 1, and Experiment 4 in Repp, 2003) did not provide much support for that hypothesis.

The results of the conditions in which the difference between mean ITI and *D*-IOI was small thus provide some support for the hypothesis that taps can be attracted directly to *D* tones, but the attraction is relatively weak, intermittent, and not necessarily towards a precise in-phase relationship. It can be recognized as an instance of *relative coordination* or *intermittency*, as described in the dynamic systems literature (e.g., Kelso, 1995), and as observed in the visual coordination studies of Schmidt and O'Brien (1997) and Richardson et al. (2005). This phenomenon is often observed in cases of *symmetry breaking*, for example when two periodic processes with different natural frequencies are to be coordinated. In the present case, symmetry breaking presumably was enhanced by the intention to avoid coordination, because intermittency rather than synchronization occurred even when the tapping and distractor periods were nearly identical. If synchronization had been the participants' goal, it would have been trivial for them to adjust the phase and period of their tapping to arrive at an in-phase relationship with the *D* sequence. Given the intention to avoid any such coordination, however, involuntary intermittent coordination occurred most often in those

nearly symmetric cases where the period of the *D* sequence (the IOI) was most similar to the tapping period (the ITIs). When such coordination occurred, participants probably noticed it and changed their tapping period to pull away from the *D* sequence. It should be noted that there was hardly any tendency to be drawn into an intermittent anti-phase relationship with the *D* sequence (i.e., there were no peaks at the edges of the graphs in Fig. 8). Apparently, that alternative attractor was too weak to overcome participants' intention not to be affected by the *D* sequence.

The observed shifts of the preferred phase relationship away from the in-phase relationship in the case of small tempo differences between the tapping and the *D* sequence are consistent with the effects of *detuning* (i.e., a difference in natural frequency) on the phase relationship between coupled oscillators (see, e.g., Pikovsky, Rosenblum, & Kurths, 2001): Both during absolute and relative coordination, the faster oscillator leads the slower oscillator. Absolute coordination occurs within the *synchronization region* or *Arnold tongue*, a region of small detuning. In the present study, where the tapping was unilaterally coupled to the *D* sequence via perception, the intention not to synchronize can be understood as entailing a radical narrowing of the Arnold tongue, so that relative coordination occurred at detunings that otherwise would permit synchronization, whereas coordination was entirely absent at detunings at which relative coordination might have occurred if the intention had been to synchronize. Actually, however, this comparison leaves out the fact that people can adjust their tapping frequency at will, so that relative coordination will hardly ever be observed when there is an intention to synchronize, except perhaps at very high frequencies. By contrast, when trying to ignore a *D* sequence, people do try to maintain the tapping tempo induced by the *T* sequence (a temporarily and voluntarily fixed frequency) and thus create a condition favorable to relative coordination. Thus, the naturally flexible tapping frequency can have effects similar to those of a fixed natural frequency when a lack of flexibility is required by the task.

The fact that the present results can be understood quite well in terms of dynamic systems theory reopens the question of whether the relationship between the periodic events is better described in terms of absolute temporal separation or relative phase. Relative phase is the parameter favored by dynamic systems theorists, but Repp (2004) obtained evidence in fixed-separation distractor experiments suggesting that absolute temporal separation between the *T* tones and *D* tones, not their relative phase, was the variable governing distractor effects. Here, the question concerns the relationship between taps and *D* tones. Although Experiment 2 was not designed to address this issue directly, a close look at Fig. 8 reveals that the peaks in the frequency distributions of asynchronies are narrower in the *T*600 condition than in the *T*400 condition. Because the *x*-axis scale represents relative phase (each tick represents 5% of the *D*-IOI), this difference means that the intermittent entrainment extended over a smaller range of relative phases in the *T*600 than in the *T*400 condition, which suggests that absolute temporal separation was also the governing parameter in the present experiment. In other words, intermittent attraction of taps to *D* tones occurred within a fixed temporal window, albeit one that changed shape as the tempo relationship between taps and the *D* sequence changed. Moreover, the

width of that window is roughly similar to the temporal window within which T tones and D tones had to occur in the fixed-separation distractor paradigm for distractor effects to emerge (i.e., 120–150 ms).

In conclusion, the present study demonstrates that people who intend to ignore an auditory distractor sequence during self-paced tapping nevertheless are influenced by it, particularly when the tempo difference between tapping and the distractor sequence is small. In that case, evidence for intermittent coordination was found. When the tempo differed by as much as 10%, intermittent coordination disappeared, a finding that contrasts with the systematic modulation of asynchronies and inter-tap intervals that occurred with similar tempo differences when the task was to synchronize with a target sequence in the presence of a distractor sequence (Experiment 1). Thus, although distractor tones can attract taps directly under certain conditions, the systematic modulation effects in a synchronization task seem to be mediated primarily by perceptual integration of target and distractor tones, which jointly engage the phase correction mechanism that maintains synchrony. Although the phase correction process is generally assumed to be inactive during self-paced tapping, it is conceivable that it was engaged intermittently by distractor tones. However, given that the tempo relationship between taps and the distractor sequence plays a role, it is possible that distractor effects during self-paced tapping are mediated by the period correction mechanism which controls phase indirectly via a modification of the tapping period (Mates, 1994; Repp, 2001b). Further research will be necessary to distinguish between these two theoretical possibilities.

So, next time you walk on the street and a marching band approaches, don't think you'll be able to escape the music entirely. You may not be aware of it, but your gait may be slightly faster, more variable, and even may be in lockstep with the beat of the bass drum from time to time. To firm up such generalizations, however, research bridging the gap between simple laboratory tasks and more complex real-life situations is still required.

Acknowledgments

References

Aschersleben, G., & Bertelson, P. (2003). Temporal ventriloquism: Crossmodal interaction on the time dimension 2. Evidence from sensorimotor synchronization. *International Journal of Psychophysiology, 50*, 157–163.

Collier, G. L., & Ogden, R. T. (2004). Adding drift to the decomposition of simple isochronous tapping: An extension of the Wing–Kristofferson model. *Journal of Experimental Psychology: Human Perception and Performance, 30*, 853–872.

Fendrich, R., & Corballis, P. M. (2001). The temporal cross-capture of audition and vision. *Perception & Psychophysics, 63*, 719–725.

Folk, C. L., & Remington, R. (1998). Selectivity in distraction by irrelevant featural singletons: Evidence for two forms of attentional capture. *Journal of Experimental Psychology: Human Perception and Performance, 24*, 847–858.

Folk, C. L., Remington, R., & Johnston, J. C. (1992). Involuntary covert orienting is contingent on attentional control settings. *Journal of Experimental Psychology: Human Perception and Performance, 18*, 1030–1044.

Hary, D., & Moore, G. P. (1985). Temporal tracking and synchronization strategies. *Human Neurobiology, 4*, 73–77.

Hary, D., & Moore, G. P. (1987). Synchronizing human movement with an external clock source. *Biological Cybernetics, 56*, 305–311.

Kelso, J. A. S. (1995). *Dynamic patterns: The self-organization of brain and behavior.* Cambridge, MA: MIT Press.

Large, E. W., Fink, P., & Kelso, J. A. S. (2002). Tracking simple and complex sequences. *Psychological Research, 66*, 3–17.

Mates, J. (1994). A model of synchronization of motor acts to a stimulus sequence. I. Timing and error corrections. *Biological Cybernetics, 70*, 463–473.

Morein-Zamir, S., Soto-Faraco, S., & Kingstone, A. (2003). Auditory capture of vision: Examining temporal ventriloquism. *Cognitive Brain Research, 17*, 154–163.

Pikovsky, A., Rosenblum, M., & Kurths, J. (2001). *Synchronization: A universal concept in nonlinear sciences.* Cambridge, UK: Cambridge University Press.

Pressing, J. (1998). Error correction processes in temporal pattern production. *Journal of Mathematical Psychology, 42*, 63–101.

Recanzone, G. H. (2003). Auditory influences on visual temporal rate perception. *Journal of Neurophysiology, 89*, 1078–1093.

Repp, B. H. (1997). Acoustics, perception, and production of legato articulation on a computer-controlled grand piano. *Journal of the Acoustical Society of America, 102*, 1878–1890.

Repp, B. H. (2000). Compensation for subliminal timing perturbations in perceptual-motor synchronization. *Psychological Research, 63*, 106–128.

Repp, B. H. (2001a). Phase correction, phase resetting, and phase shifts after subliminal timing perturbations in sensorimotor synchronization. *Journal of Experimental Psychology: Human Perception and Performance, 27*, 600–621.

Repp, B. H. (2001b). Processes underlying adaptation to tempo changes in sensorimotor synchronization. *Human Movement Science, 20*, 277–312.

Repp, B. H. (2002a). Automaticity and voluntary control of phase correction following event onset shifts in sensorimotor synchronization. *Journal of Experimental Psychology: Human Perception and Performance, 28*, 410–430.

Repp, B. H. (2002b). Phase correction in sensorimotor synchronization: Nonlinearities in voluntary and involuntary responses to perturbations. *Human Movement Science, 21*, 1–37.

Repp, B. H. (2002c). Effects of metrical structure on phase resetting in sensorimotor synchronization. In C. Stevens, D. Burnham, G. McPherson, E. Schubert, & J. Renwick (Eds.), *Proceedings of the seventh international conference on music perception and cognition* (pp. 572–574). Sydney: Causal Productions (CD-ROM).

Repp, B. H. (2003). Phase attraction in sensorimotor synchronization with auditory sequences: Effects of single and periodic distractors on synchronization accuracy. *Journal of Experimental Psychology: Human Perception and Performance, 29*, 290–309.

Repp, B. H. (2004). On the nature of phase attraction in sensorimotor synchronization with interleaved auditory sequences. *Human Movement Science, 23*, 389–413.

Repp, B. H., & Keller, P. E. (2004). Adaptation to tempo changes in sensorimotor synchronization: Effects of intention, attention, and awareness. *Quarterly Journal of Experimental Psychology A, 57*, 499–521.

Repp, B. H., & Penel, A. (2002). Auditory dominance in temporal processing: New evidence from synchronization with simultaneous visual and auditory sequences. *Journal of Experimental Psychology: Human Perception and Performance, 28*, 1085–1099.

Repp, B. H., & Penel, A. (2004). Rhythmic movement is attracted more strongly to auditory than to visual rhythms. *Psychological Research, 68*, 252–270.

Richardson, M. J., Marsh, K., & Schmidt, R. C. (2005). Effects of visual and verbal interaction on unintentional interpersonal coordination. *Journal of Experimental Psychology: Human Perception and Performance, 31*, 62–79.

Schmidt, R. C., & O'Brien, B. (1997). Evaluating the dynamics of unintended interpersonal coordination. *Ecological Psychology, 9*, 189–206.

Semjen, A., Schulze, H.-H., & Vorberg, D. (2000). Timing precision in continuation and synchronization tapping. *Psychological Research, 63*, 137–147.

Stevens, L. T. (1886). On the time-sense. *Mind, 11*, 393–404.

Vorberg, D., & Schulze, H.-H. (2002). A two-level timing model for synchronization. *Journal of Mathematical Psychology, 46*, 56–87.

Wing, A. M., & Kristofferson, A. B. (1973). The timing of interresponse intervals. *Perception & Psychophysics, 13*, 455–460.