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Human Movement Science 23 (2004) 389–413

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On the nature of phase attraction in sensorimotor synchronization with interleaved auditory sequences

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Abstract

In a task that requires in-phase synchronization of finger taps with an isochronous sequence of target tones that is interleaved with a sequence of distractor tones at various fixed phase relationships, the taps tend to be attracted to the distractor tones, especially when the distractor tones closely precede the target tones [Repp, B. H. (2003a). 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]. The present research addressed two related questions about this distractor effect: (1) Is it a function of the absolute temporal separation or of the relative phase of the two stimulus sequences? (2) Is it the result of perceptual grouping (integration) of target and distractor tones or of simultaneous attraction to two independent sequences? In three experiments, distractor effects were compared across two different sequence rates. The results suggest that absolute temporal separation, not relative phase, is the critical variable. Experiment 3 also included an anti-phase tapping task that addressed the second question directly. The results suggest that the attraction of taps to distractor tones is caused mainly by temporal integration of target and distractor tones within a fixed window of 100–150 ms duration, with the earlier-occurring tone being weighted more strongly than the later-occurring one.

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0167-9457/$ - see front matter
doi:10.1016/j.humov.2004.08.014

Keywords: Synchronization; Tapping; Relative phase; Temporal integration; Phase attraction; Perceptual grouping

1. Introduction

Perception of auditory temporal patterns can undergo qualitative changes as a function of tempo. Some of these changes occur when certain critical intervals of temporal integration are reached or exceeded. For example, one such critical interval, variously described as being between 1.5 and 3 s in duration, limits the perception of rhythmic coherence in a regular sequence of tones. If the tones are separated by longer intervals, intentional or spontaneous perception of the sequence as a rhythm becomes impossible (Bolton, 1894; Fraisse, 1982; MacDougall, 1903; Szelag, von Steinbüchel, Reiser, de Lange, & Pöppel, 1996), and the anticipation required in a synchronization task turns into reaction to successive events (Engström, Kelso, & Holroyd, 1996; Klemmer, 1967; Mates, Radil, Müller, & Pöppel, 1994). The interval of 1.5–3 s is considered to represent the duration of the subjective (or psychological) present (Fraisse, 1984; Pöppel, 1997) within which durations can be perceived directly rather than having to be estimated from memory traces (Fraisse, 1984). A number of other phenomena related to this relatively long critical interval have been noted (see Pöppel, 1996, 1997; Wittmann, 1999; Wittmann & Pöppel, 1999–2000).

At the other extreme, some very short intervals have been hypothesized to constitute the periods of oscillatory brain mechanisms. For example, Pöppel (1996, 1997) has argued that rapid oscillations with a period of 30 ms underlie the ability to perceive temporal succession: If event onsets occur at shorter temporal separations, they are perceived as simultaneous (cf. Hirsh & Sherrick, 1961). An even shorter time quantum of 4.5 ms has been envisioned by Geissler (Geissler, 1987, 1997; Geissler & Kompass, 2001) and has been linked to the concept of neural "synfire chains" (Kompass, 2004).

Additional integration windows may exist between these extremes on the time continuum, perhaps reflecting different levels in an ascending processing chain. The present study is concerned with one such hypothesized window whose duration is 100–150 ms, and which may be specific to auditory perception. There is evidence from a variety of tasks that auditory events whose onsets are separated by less than 100–150 ms tend to be tightly integrated and grouped together, so that they can no longer be attended to as individual events, even though they are clearly perceived as distinct and successive.

For example, van Noorden (1975), in his classic studies of auditory stream segregation, determined that the "temporal coherence boundary" and the "fission boundary" converged when cyclically repeated tones of different pitch were separated by less than 100 ms (see Bregman, 1990, Figure 2.2). This convergence implies that the percept of one stream versus two streams of tones (i.e., temporal coherence versus fission) depends entirely on the pitch difference between the tones, and not on the listener's intentions. At temporal separations greater than 100 ms, the two boundaries diverge, which means that tones of different pitch can be heard at will as forming either one or two streams, unless the pitch difference is very large or very small.

Yabe, Tervaniemi, Reinikainen, and Näätänen (1997, 1998) investigated the mismatch negativity (MMN) component of event-related brain potentials in response to single omitted tones in a sequence. A MMN was observed only when the tone onsets were separated by less than 150 ms. The MMN is believed to be an automatic response of the auditory cortex to a stimulus change (Näätänen & Winkler, 1999), and Yabe et al. interpreted their results as reflecting a temporal integration window within which two successive tones are treated as a single event, so that omission of one tone results in perception of a change in event structure (rather than just in event timing).

A number of other phenomena in that temporal range could be mentioned. For example, Efron (1970, 1973) has obtained response latency and cross-modal matching data suggesting that stimuli with durations of less than 130 ms have an effective perceptual duration of about 130 ms. More recently, neurophysiological studies have investigated the gamma-band response evoked by auditory stimuli, which is believed to play a role in the binding of stimulus attributes. These oscillations typically last for about 100 ms and thus may provide a basis for the integration of successive stimuli as well (see, e.g., Knief, Schulte, Bertrand, & Pantev, 2000). Auditory forward masking extends over similar intervals and may reflect a related temporal integration process (Oxenham, 2001).

Most relevant to the present study is the finding that synchronization of finger taps with selected tones in an isochronous sequence is possible only up to a sequence rate of 8–10 Hz (Bartlett & Bartlett, 1959; Repp, 2003b). If the tone onsets are separated by less than 100–125 ms, phase drift occurs, typically without the participant's awareness. It appears that individual tones can no longer be singled out as attentional targets at these high rates. Closely related findings are that errors in covert counting of tones (up to 10) begin to appear when the sequence rate exceeds 8 Hz (Massaro, 1976; Taubman, 1950), and that subjective grouping of tones in an isochronous sequence is no longer possible when the separation between tones is less than about 115 ms (Bolton, 1894).

These findings are relevant to music perception and performance. London (2002, 2004) and Iyer (2002) have recently suggested that the smallest possible metrical subdivision in music, the "tatum" (Bilmes, 1993), is about 100 ms in duration. Measurements of the swing rhythm in jazz performances, as played by percussionists at various tempi, have indicated that the inter-onset intervals (IOIs) between drum beats reach a lower limit of about 100 ms (Friberg & Sundström, 2002). Although tones separated by shorter IOIs can be found in music performance, they do not function as independent components of a rhythmic pattern but rather as ornaments or arpeggios that are attached to adjacent tones (e.g., Repp, 1997; Timmers, Ashley, Desain, Honing, & Windsor, 2002). It may also be relevant that, although IOIs as short as 100 ms cannot be achieved in continuous tapping with a single finger, tapping with alternating hands seems to be possible just up to about that rate (Pressing & Jolley-Rogers, 1997).

The present study investigated whether this short integration interval is the underlying reason for a striking phenomenon observed in a recent study of sensorimotor synchronization (Repp, 2003a: Experiment 2). In that experiment, participants attempted to synchronize finger taps with an isochronous target tone sequence (IOI = 500 ms) in the presence of a distractor sequence, composed of tones of different pitch. The distractor sequence had the same constant IOI duration but, in different trials, occurred at a number of different temporal relationships (or relative phases) with the target sequence. The results showed that participants' taps were strongly attracted to leading distractor tones, but only weakly to lagging ones. The attraction to leading distractor tones was strong up to 80 ms of lead time but much weaker at 160 ms of lead time. Although the experimental design did not include lead times between these two values, the results are consistent with an integration interval of 100–150 ms duration, within which the leading tone is more salient than the lagging tone.

The stimulus sequences employed in that experiment were structurally similar to those often used as pacing sequences in studies of bimanual coordination, although these studies have more often used two alternating lights than tones of different pitch (e.g., Kelso & Zanone, 2002; Semjen & Ivry, 2001; Tuller & Kelso, 1989; Yamanishi, Kawato, & Suzuki, 1980; Zanone & Kelso, 1992, 1997). Bimanual coordination studies, with the significant recent exception of Semjen and Ivry (2001), have typically taken a dynamical systems approach, according to which the principal controlled variable is relative phase. Thus, two interleaved pacing sequences varying in relative phase were presented, and participants moved their hands or arms at corresponding relative phases by synchronizing the movements with the respective stimulus sequences, more or less successfully. Relative phase is measured in degrees of phase angle or as a proportion of the period, not in absolute milliseconds. Behavioral results are expected (and often found) to be similar at the same relative phase across changes in tempo (frequency), where the same relative phase represents different absolute stimulus IOIs and response IOIs. Exceptions to this rule are abrupt phase transitions that occur when rate limits of stability are reached for certain coordination patterns, such as anti-phase movement.

The task used in Experiment 2 of Repp (2003a) and in the present study differs from bimanual coordination tasks in that the response is unimanual and is to be synchronized with only one of the two interleaved stimulus sequences, the target sequence, while the other sequence, the distractor sequence, is to be ignored. Nevertheless, the target and distractor sequences can be described as varying in their relative phase, and Repp even used the term *phase attraction* to describe the effect of the target and distractor tones on the taps. However, he had no direct evidence that relative phase was indeed the critical variable, because only a single sequence rate (IOI = 500 ms) was employed. The present study examined whether the attraction of taps to distractor tones is governed by the relative phase or by the absolute temporal separation of target and distractor tones. To that end, it assessed distractor effects at different sequence rates and examined whether the results are more similar when plotted as a function of the absolute interval between target and distractor tones or when plotted as a function of the relative phase between target and distractor sequences.

If the distractor effects were governed by relative phase, then the temporal separation over which they extend should expand or contract in proportion to IOI duration. Such a result would argue against a hard-wired perceptual integration interval, whereas it could easily be interpreted within a dynamical systems framework, for example by considering the target and distractor sequences as external oscillators that drive the motor activity with different strengths of sensorimotor coupling (see, e.g., Wimmers, Beek, & van Wieringen, 1992). If the temporal range of distractor effects were found to be constant, this would support the perceptual integration hypothesis but would not necessarily be inconsistent with a dynamical systems view, because the neural mechanisms underlying perceptual integration (e.g., gamma oscillations) can be considered as dynamic processes in their own right. It would be inconsistent, however, with the specific prediction that the relative phase of the stimulus sequences is the variable governing the distractor effects. That prediction would seem to follow most naturally from a dynamical systems view.

Three experiments were conducted, the third of which included an additional condition (anti-phase tapping) intended to provide a more direct test of whether the distractor effects represent attraction to integrated perceptual representations of target and distractor tones or to independent target and distractor tones. The rationale of that test is presented in the introduction to Experiment 3.

2. Experiment 1

The purpose of Experiment 1 was to replicate the distractor effects (Repp, 2003a: Experiment 2) at two different sequence tempi, one faster and the other slower than the previously used tempo. Because attraction to distractor tones in the earlier study was pronounced only when the distractor tones led the target tones, Experiment 1 focused on that condition exclusively. Target and distractor sequences were presented at a number of temporal separations, such that these absolute separations (rather than the corresponding relative phases) were the same at the two tempi. (The alternative design was used in Experiments 2 and 3.) The question of interest was whether the asynchronies between taps and target tones at the two tempi would be more similar when plotted as a function of the absolute temporal separation of target and distractor tones or when plotted as a function of their relative phase.

2.1. Methods

2.1.1. Participants

Seven paid volunteers (5 women, 2 men) and the author participated. Two participants (one being the author) were both 57 years old at the time; the ages of the others ranged from 18 to 30. All were musically trained: Two were professional musicians, and the others were advanced amateurs with 10 or more years of training on an instrument. Except for one of the professional musicians, all were regular participants in synchronization experiments.

2.1.2. Materials and equipment

The stimulus sequences were composed of high-pitch digital piano tones which had a sharp attack and decayed rapidly (within about 100 ms). The tones were produced on a Roland RD-250s digital piano under control of a MAX patch running on a Macintosh Quadra 660AV computer connected to the piano via a musical instrument digital interface (MIDI) translator. [1] Tones of different pitch were used in the target and distractor sequences, with the target tones being assigned either the higher or the lower pitch. The pitches were E7 (MIDI pitch 100, about 2640 Hz) and G7 (MIDI pitch 103, about 3136 Hz), a separation of 3 semitones. All tones were produced at the same nominal intensity (i.e., MIDI key velocity). Successive tone onsets within each sequence were separated by 360 ms in the fast tempo condition and by 720 ms in the slow tempo condition.

Each trial consisted of interleaved target and distractor sequences. The target sequence contained 26 tones, the distractor sequence 20. The target sequence started first, and the distractor sequence came in before the seventh target tone at one of 10 possible temporal separations which ranged from 0 to −180 ms in steps of −20 ms. The values are negative to indicate that the distractor tones preceded the target tones. The normalized relative phases of the target and distractor sequences (i.e., their temporal separation divided by the target sequence IOI) thus ranged from 0 (in-phase) to −0.5 (anti-phase) at the fast tempo, and from 0 to −0.25 at the slow tempo.

Two pitch assignments and 10 temporal separations resulted in 20 trials that were presented in blocks, with a different random order in each block. There were 10 blocks in the fast tempo condition, and 8 in the slow tempo condition.

2.1.3. Procedure

The experiment was divided into two sessions, one for each tempo condition. The fast tempo condition lasted less than one hour, the slow tempo condition a little longer than one hour. The order of the tempo conditions was counterbalanced. Participants sat in front of a 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. Most participants tapped with the index finger of the right hand (all were right-handed), while the wrist and the other fingers rested on the pad. One participant (an amateur drummer), tapped "from above" with the middle finger of the unsupported right hand, using movements of wrist and elbow. Participants were instructed to start tapping with the third target tone and to continue tapping in synchrony with the target tones while ignoring the distractor tones. They were informed that the target tones could have either the higher or the lower pitch, and that the distractor tones would always precede the target

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[1] A MAX patch is a program written in the graphical programming language MAX. Due to a peculiarity of this software (Version 3.0) on the computer used, 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. Throughout this article, all millisecond values are reported as they appeared in the MAX environment. Apart from the constant scaling factor, MAX was highly accurate (within 1 ms) in timing the sequences and registering the key presses. Note that relative phase values are unaffected by the scaling.

tones. It was also pointed out that it was important to remember the pitch of the target tones, and that the final tone of each trial would always be a target tone. In case a participant noticed that he or she had synchronized with the wrong sequence, the trial was to be repeated by clicking a "repeat" button on the computer screen. (This option was used infrequently.)

The sessions were self-paced. Participants started a block by clicking a "start" button on the screen and initiated each subsequent trial by pressing the space bar of the computer keyboard. There was a 2-s delay before the next 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

The asynchronies between taps and target tones were inspected for anomalies. Although attraction to a distractor sequence was not an anomaly, there were a few instances (a total of 4 trials) in which the asynchronies of a single trial differed radically from all other repetitions of that trial type and showed a pattern suggesting that the participant had mistaken the distractor sequence for the target sequence. The data for these outlier trials were deleted. In a similarly small number of instances, outlier asynchronies suggesting lapses of attention within a trial were deleted, but the other data from that trial were retained. Because the attraction to distractor tones takes a few taps to reach its maximum (see Repp, 2003a: Fig. 5), only the asynchronies from taps 15–24 were analyzed. These were the taps coinciding with the last 10 target tones. From these data, the mean asynchrony and the standard deviation were calculated for each trial, and these were then averaged across all trials of the same type (10 at the fast tempo, 8 at the slow tempo) for each participant, and eventually across all participants.

To present the average data with standard errors that reflect only the variability of the distractor effect and not also individual differences in the absolute magnitude of the mean asynchronies (which are of little interest in the present context), each participant's asynchronies were expressed as deviations from his or her mean baseline asynchrony, defined as the one for coinciding target and distractor sequences. This computation of *relative asynchronies* was done separately in each of the four conditions resulting from the crossing of two tempi and two pitch assignments, so that baseline differences between these conditions were eliminated. The discussion of results begins with these baseline differences and then proceeds to the main results.

2.2. Results and discussion

The mean asynchronies in the baseline condition (temporal separation = 0 ms) were subjected to a 2×2 repeated-measures ANOVA, with the variables of tempo and target pitch. There were no significant effects. The average asynchronies were -0.4 ms and -2.2 ms at the fast and slow tempo, respectively. (A negative mean asynchrony indicates that taps tended to precede tones.) Thus, the anticipation tendency typically found in synchronization tasks (see, e.g., Aschersleben, 2002) was virtually absent, and the usual increase in that tendency with a slowing of tempo (e.g., Mates et al., 1994) was absent as well. This may have been due to the extensive musical training and tapping experience of the participants. Individual mean baseline asynchronies ranged from −13 ms to 29 ms. The mean within-trial standard deviations of the baseline asynchronies were entered into a similar 2 × 2 ANOVA. Again, pitch had no effect, but variability was significantly smaller at the fast tempo than at the slow tempo, $F(1,7) = 63.5$, $p < 0.001$, as had been fully expected. The average standard deviations were 11.5 ms and 19.4 ms, respectively.

The main results are shown in Fig. 1. Fig. 1A plots the relative asynchronies in the two tempo conditions, averaged over pitch assignments and participants, as a function of normalized relative phase, whereas Fig. 1B plots the same data as a function of target–distractor separation in milliseconds, the dimension that was nominally manipulated. Although the results for the two tempo conditions do not coincide exactly in Fig. 1B, they certainly look more similar there than in Fig. 1A. The linear correlation between the two functions in Fig. 1B is 0.91 (d.f. = 8, $p < 0.001$), whereas the correlation in Fig. 1A, calculated after linear interpolation between the data points for the faster tempo, is −.02.

The dip in each function represents the expected distractor effect. It was maximal when the distractors led by 60–80 ms and extended over approximately 120 ms at each tempo. To determine whether there were any significant differences between conditions, the relative asynchronies were entered into a 10 × 2 × 2 repeated-measures ANOVA, with the variables of temporal separation, tempo (IOI), and pitch. The Greenhouse-Geisser correction was applied to effects involving temporal separation, and the value of ϵ is reported. There was a significant main effect of temporal separation, $F(9,63) = 19.6$, $p < 0.001$, $\varepsilon = 0.21$, which showed the distractor effect to be reliable overall. The only other effect to reach significance was the main effect of pitch, $F(1,7) = 6.1$, $p < 0.05$: Attraction to distractors was weaker when the target pitch was low than when it was high, especially at the slow tempo, although the Pitch × Tempo interaction was not significant. No effect involving tempo was significant. Thus, the results for the two tempo conditions were statistically equivalent when considered as a function of absolute temporal separation (Fig. 1B).

These results clearly favor the hypothesis that the absolute temporal separation rather than the relative phase of the target and distractor sequences is the variable governing the distractor effect. The results are consistent with the hypothesis of a fixed temporal integration interval of less than 120 ms duration. It might be argued that, in fairness to the alternative hypothesis, the data in Fig. 1A should not have been plotted as relative asynchronies but as relative phases between taps and target tones. It is obvious, however, that this would not have affected the conclusions. In particular, the range over which the distractor effect extends at each tempo would have remained the same, given that the mean baseline asynchronies were close to zero. Only the magnitude of the effect would have seemed much smaller at the slow than at the fast tempo, which arguably would have been a misleading representation of the data. It seems more reasonable to conclude from Fig. 1 that the distractor effect was about equally strong in both tempo conditions.

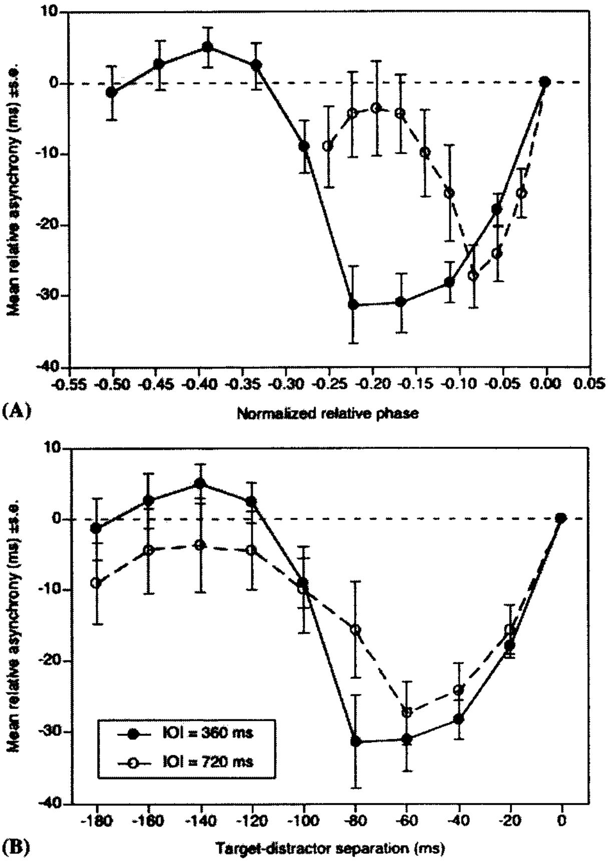

Fig. 1. Experiment 1: Average relative asynchrony for two sequence tempi (A) as a function of relative phase and (B) as a function of target–distractor separation.

Fig. 2 shows the average within-trial standard deviations of the asynchronies, plotted in two different ways, analogous to Fig. 1. An ANOVA on these data revealed a large main effect of tempo, $F(1, 7) = 222.5$, $p < 0.001$, as well as a main effect of temporal separation, $F(9, 63) = 6.1$, $p < 0.008$, $\varepsilon = 0.28$, and an interaction between these two variables, $F(9, 63) = 3.9$, $p < 0.02$, $\varepsilon = 0.37$. It can be seen that, in addition to being more variable, the asynchronies at the slow tempo exhibited a peak in variability around −80 ms of target–distractor separation, whereas the standard deviations at the fast tempo show a mere hint of a peak at −100 ms. Although the patterns of variability at the two tempi differ when plotted as a function of temporal separation (Fig. 2B), they are much more dissimilar when they are plotted as a function of relative phase (Fig. 2A). The linear correlation between the two functions in Fig. 2B is 0.57 (d.f. = 8, $p < 0.10$), whereas that in Fig. 2A (after linear interpolation of the function for the fast tempo) is −.39 (n.s.).

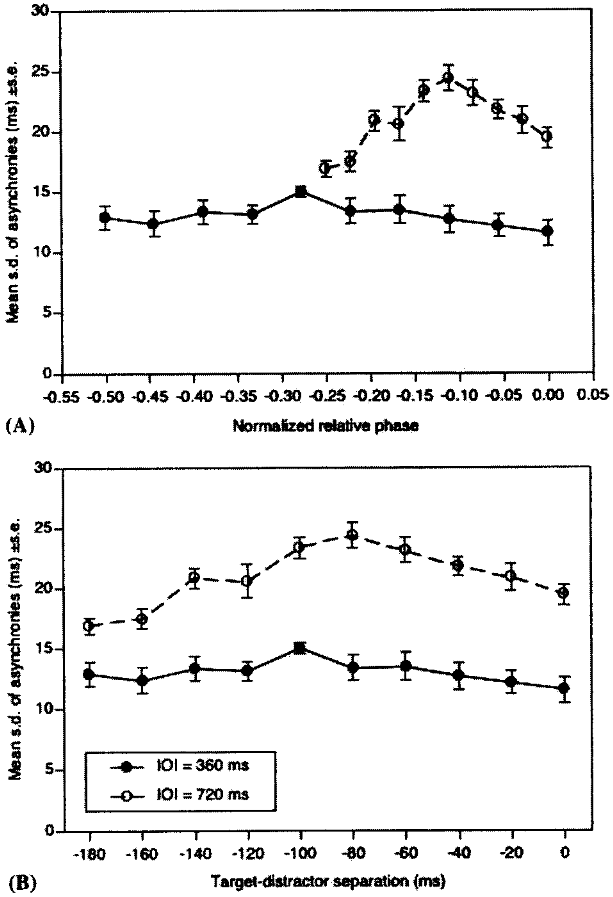

Fig. 2. Experiment 1: Average standard deviation of asynchronies for two sequence tempi (A) as a function of relative phase and (B) as a function of target–distractor separation.

3. Experiment 2

Experiment 2 had the same purpose as Experiment 1 but differed in three respects. First, instead of equating the target–distractor separations across two tempi, Experiment 2 equated the relative phases. This was done to make sure that the results of Experiment 1 were not an artifact of the different ranges of relative phases at the two tempi. Second, Experiment 2 included both leading and lagging distractors, to replicate more closely the original experiment by Repp (2003a). Third, the difference between the two tempi was smaller than in Experiment 1. [2]

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[2] The reason for this last change was not profound: The IOI durations were chosen to yield round millisecond values for the temporal separations corresponding to the various relative phases.

3.1. Methods

3.1.1. Participants

Six of the 8 participants were the same as in Experiment 1. The two new participants (1 woman, 1 man) were similar in age, musical training, and task experience to the two earlier same-sex participants whom they replaced.

3.1.2. Materials and equipment

The sequences were of the same general construction and composed of the same tones as in Experiment 1. The IOIs within sequences were 400 ms (fast tempo) and 600 ms (slow tempo). At each tempo, the target and distractor sequences were presented at the following 10 normalized relative phases: 0, ±0.08, ±0.16, ±0.24, ±0.32, and 0.5. Thus, at the fast tempo the temporal separations were 0, ±32, ±64, ±96, ±128, and 200 ms, whereas at the slow tempo they were 0, ±48, ±96, ±144, ±192, and 300 ms. When the distractor tones lagged behind the target tones, an extra target tone was added at the end of the sequence, so participants could check that they had synchronized with the correct sequence and could repeat the trial, if necessary.

Two pitch assignments and 10 relative phases resulted in 20 trials that were presented in blocks, with a different random order in each block. There were 10 blocks in the fast tempo condition, and 8 in the slow tempo condition.

3.1.3. Procedure

The procedure was the same as in Experiment 1. Again, the two tempo conditions were run in separate sessions whose order was counterbalanced across participants. Participants were informed that the distractor tones could either precede or follow the target tones.

3.1.4. Analysis

Before analyzing the data in the same way as in Experiment 1, four trials were removed as outliers, and a small number of deviant individual asynchronies was edited out.

3.2. Results and discussion

As in Experiment 1, neither tempo nor target pitch had any significant effect on the mean asynchronies in the baseline condition (coinciding target and distractor tones). In contrast to Experiment 1, however, an anticipation tendency was present: The average asynchronies were −13.9 ms and −16.8 ms at the fast and slow tempo, respectively. Individual mean baseline asynchronies ranged from −33 ms to −6 ms. An ANOVA on the mean within-trial standard deviations of the baseline asynchronies showed, in agreement with Experiment 1, that variability was significantly smaller at the fast tempo than at the slow tempo, $F(1, 7) = 6.2$, $p < 0.05$, although the difference was less reliable than in Experiment 1, probably because of the smaller tempo difference. The average baseline standard deviations at the fast and slow tempi were 12.7 ms and 15.6 ms, respectively.

The main results are shown in Fig. 3. The upper panel plots the relative asynchronies as a function of relative phase, the dimension that was nominally manipulated, whereas the lower panel plots the same data as a function of temporal separation. The data for a relative phase of 0.5 are duplicated at a relative phase of −0.5. As expected on the basis of earlier findings (Repp, 2003a), the effect of leading distractors was larger than that of lagging distractors, especially at the slower tempo. The temporal range of the effect, about 150 ms, was somewhat larger than in Experiment 1. Even though Experiment 2 was designed to equate the relative phases across the two tempi, it is again clear that the data are better aligned when they are plotted in terms of temporal separation (Fig. 3B) than in terms of relative phase (Fig. 3A). The correlation between the functions in Fig. 3A is 0.50 (n.s.), whereas that in Fig. 3B

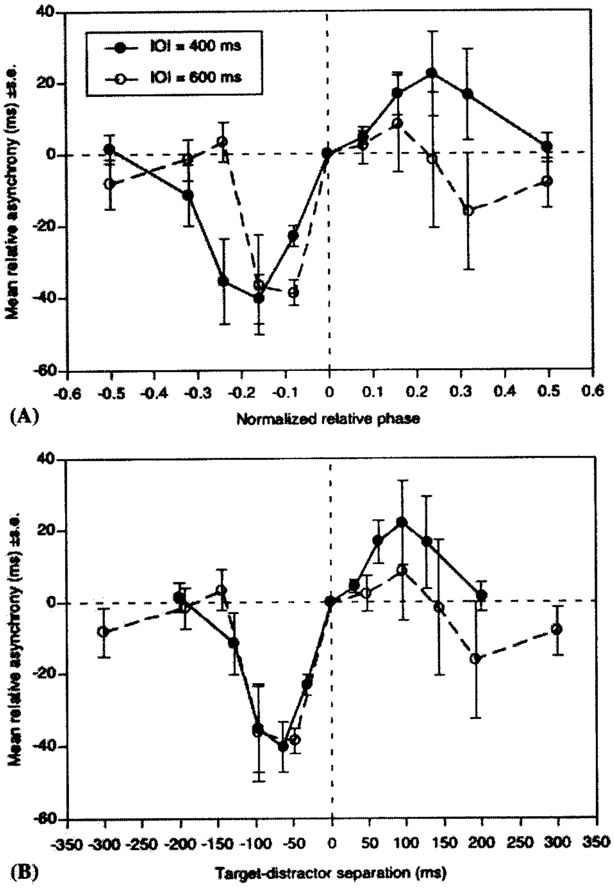

Fig. 3. Experiment 2: Average relative asynchrony for two sequence tempi (A) as a function of relative phase and (B) as a function of target–distractor separation.

(after linear interpolation of the function for IOI = 600 ms) is 0.95 (d.f. = 8, $p < 0.001$). Moreover, the temporal range of the distractor effect appears constant in Fig. 3B, but not in Fig. 3A.

The ANOVA on the relative asynchronies, with the factors of relative phase, tempo, and target pitch, showed a significant main effect of relative phase, $F(9, 63) = 7.0$, $p < 0.007$, $\varepsilon = 0.24$, which indicates that the phase attraction effect is reliable. In addition, however, there was a significant interaction of relative phase and tempo, $F(9, 63) = 4.5$, $p < 0.02$, $\varepsilon = 0.31$, reflecting the misalignment of the data for the two different tempi when considered as a function of relative phase (Fig. 3A). Although there was no main effect of pitch, this variable interacted with relative phase, $F(9, 63) = 3.3$, $p < 0.05$, $\varepsilon = 0.32$: Both negative and positive distractor effects tended to be stronger when the target pitch was low than when it was high. This

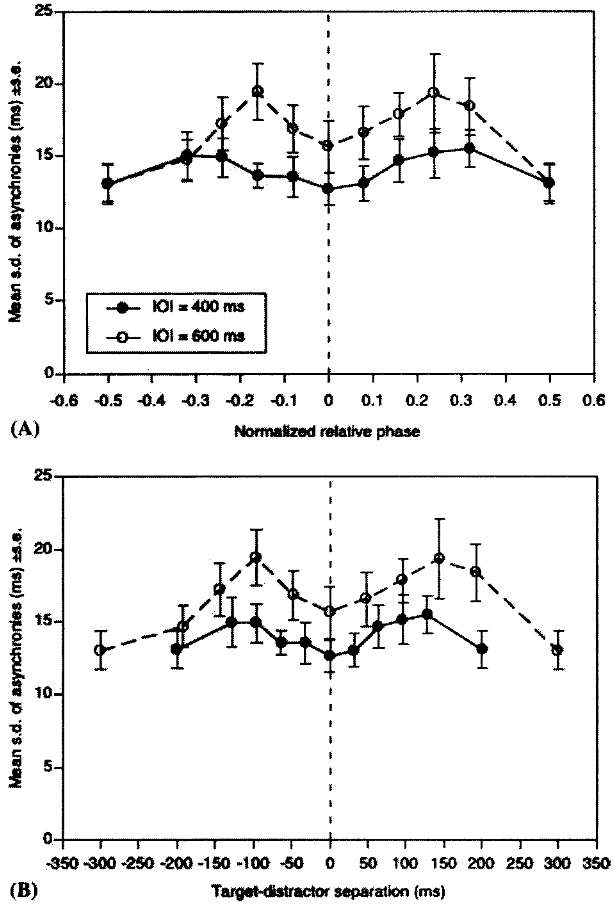

Fig. 4. Experiment 2: Average standard deviation of asynchronies for two sequence tempi (A) as a function of relative phase and (B) as a function of target–distractor separation.

effect was surprising because it was contrary to the effect of pitch in Experiment 1. Pitch also interacted with tempo, $F(1, 7) = 12.7$, $p < 0.01$, apparently because, at the slow tempo, pitch affected attraction to lagging but not to leading distractors. The triple interaction was not significant, however.

These results replicate and extend the main findings of Experiment 1, and thus provide further support for the hypothesis of a fixed perceptual integration interval. Again, this conclusion would not have been changed by plotting the data in Fig. 3A as relative phases between taps and target tones rather than as relative asynchronies. Although the baseline asynchronies were not zero in this experiment, they were unaffected by sequence tempo, which in itself contradicts the hypothesis that relative phases are invariant. Moreover, computing relative phases after adding this constant to the asynchronies would not eliminate the difference in the (relative phase) range of the distractor effect between the two tempo conditions, whereas the magnitude of the effect would seem smaller at the slow than at the fast tempo. Fig. 3B suggests, on the contrary, that the distractor effect is virtually independent of sequence tempo, at least for the tempi used here.

The average within-trial standard deviations of the asynchronies are plotted in Fig. 4. Variability was greater at the slower tempo, although this difference was only marginally significant, $F(1, 7) = 5.6$, $p = 0.05$. Relative phase had a reliable main effect, $F(9, 63) = 6.7$, $p < 0.006$, $\varepsilon = 0.27$: At both tempi, variability was low in the in-phase (0) and anti-phase (±0.5) conditions, and higher in between. This effect was more pronounced at the slower tempo, but the interaction with tempo fell short of significance, $F(9, 63) = 3.0$, $p < 0.06$, $\varepsilon = 0.34$. The alignment of the variability peaks on the negative side seems better when the data are plotted as a function of target–distractor separation (Fig. 4B), whereas the situation is less clear on the positive side. The correlation between the functions in Fig. 4A is 0.51 (n.s.), whereas that in Fig. 4B (after linear interpolation) is 0.62 (d.f. = 8, $p < 0.10$). This comparison does not contribute much to supporting one or the other hypothesis.

4. Experiment 3

The results of Experiment 1 and 2 support the perceptual integration hypothesis because it is that hypothesis which assumes that absolute temporal separation of target and distractor tones is the critical variable. However, the alternative hypothesis, according to which the target and distractor tones independently attract the taps, could be modified by adding the assumption that attraction occurs only within a critical (fixed) temporal range. These two hypotheses – perceptual integration versus range-limited attraction – would be difficult to distinguish in an in-phase tapping task. However, they make very different predictions for an anti-phase tapping task. According to the perceptual integration hypothesis, anti-phase tapping data should look similar to in-phase tapping data because in both tasks coordination occurs with reference to the same integrated representation of target and distractor tones. That is, when the distractor tones closely precede or follow the target tones, anti-phase taps should be advanced or delayed, respectively, but when the distractor tones fall near the middle of the IOI between target tones, anti-phase taps should not be affected, even though they are physically close to the distractor tones. The alternative hypothesis of attraction to independent target and distractor tones predicts just the opposite: Taps should be attracted to distractor tones that closely precede or follow them, but not to distractor tones that closely precede or follow target tones. Thus, the pattern of relative asynchronies as a function of relative phase for anti-phase tapping should be phase-shifted by 0.5 relative to the pattern for in-phase tapping. A third possibility is that, whereas perceptual integration occurs when target and distractor tones are close, attraction to independent distractor tones occurs when they are distant from the target tones but close to the taps. In that case, the asynchrony function for anti-phase tapping should show features of both the function for in-phase tapping and its phase-shifted copy.

One crucial assumption that must be granted is that, when participants tap in anti-phase with the target tones, they are still attracted involuntarily toward an *in-phase* relationship with the distractor tones. If there were good reasons for believing that the intention to tap in anti-phase with target tones causes the taps to be attracted toward an anti-phase relationship with distractor tones as well, then the predictions would not hold. However, it seems reasonable to assume that the task requirements affect only the intentional task strategy, not the automatic attraction to distractor tones, if it exists.

Experiment 3 thus included both in-phase and anti-phase tapping tasks. The in-phase tapping task constituted yet another variation on the theme of Experiments 1 and 2. To reduce the number of trials, the pitch assignment variable was dropped: Target tones always had a higher pitch than distractor tones. Furthermore, the pitch difference between target and distractor tones was increased from 3 to 8 semitones. Both of these manipulations were intended to reduce possible confusion between target and distractor sequences in the anti-phase tapping task. However, the distractor effect was expected to persist because pitch separation (3 versus 20 semitones) had little effect in the earlier study (Repp, 2003a). Additional design changes relative to Experiment 2 were that trials representing the two different sequence tempi were randomly intermixed rather than blocked, and that the relative phases were equally spaced between 0 and ±0.5.

4.1. Methods

4.1.1. Participants

Five of the 7 participants had also participated in Experiment 2. The two new participants were both percussionists (one professional and one amateur). Like the others, they were regular participants in synchronization experiments. The data of one additional participant were not analyzed because he tapped too lightly, so that many of his taps were not registered.

4.1.2. Materials

The sequences were similar to those in Experiment 2, except for the pitch of the tones and the relative phase values. Target tones always had a pitch of G7 (MIDI pitch 103, about 3136 Hz), whereas distractor tones had a pitch of B6 (MIDI pitch 95, about 1976 Hz), a separation of 8 semitones. The nominal intensity (MIDI velocity) of target and distractor tones was the same. The relative phases were 0, ±0.1, ±0.2, ±0.3, ±0.4, and 0.5. This corresponded to temporal separations of 0, ±40, ±80, ±120, ±160, and 200 ms in sequences with IOI = 400 ms, and 0, ±60, ±120, ±180, ±240, and 300 ms in sequences with IOI = 600 ms. The sequences were presented in 10 blocks of 20 randomly ordered trials each, representing 10 relative phases at each of two tempi.

4.1.3. Procedure

The experiment consisted of two one-hour sessions, requiring in-phase and anti-phase tapping, respectively, with the target tones. The sessions were typically one week apart. The procedure was the same as in Experiment 2.

4.1.4. Analysis

Not surprisingly, anti-phase tapping was more difficult than in-phase tapping in the presence of distractor tones. Occasionally, phase drift occurred. Phase drift was defined as any asynchrony that exceeded ±IOI/2; usually, such an asynchrony was followed by even larger asynchronies. The asynchronies in anti-phase tapping were calculated relative to the midpoints of the target sequence IOIs. Trials exhibiting phase drift were excluded from the calculation of mean asynchronies and standard deviations. One participant (the one with the least amount of musical training) had 40 drift trials (20% of all her trials); nevertheless, a sufficient number of successful trials remained in each condition for mean asynchronies and standard deviations to be computed. The other participants each had only between 0 and 6 drift trials. Their drift was usually negative, indicating an acceleration of tapping, whereas that of the single participant with many drift trials was usually positive, indicating deceleration. The large majority of the drift trials occurred at the faster tempo, and they tended to occur at large relative phases between target and distractor tones. This observation already suggests that distractor tones close to the taps did not constitute strong attractors, for if they did, they should have stabilized anti-phase tapping, albeit with a constant phase shift (distractor effect) at relative phases other than 0.5.

4.2. Results and discussion

The baseline asynchronies were small. A 2 × 2 ANOVA with the variables of task (in-phase, anti-phase) and tempo yielded no significant effects, although the interaction approached significance, $F(1, 6) = 5.8, p < 0.06$. The average asynchronies at the fast and slow tempi were −7.7 ms and −3.7 ms, respectively, for in-phase tapping, and 5.4 ms and −10.9 ms, respectively, for anti-phase tapping. A similar ANOVA on the baseline within-trial standard deviations of the asynchronies likewise showed no significant effects. Although the variability of in-phase tapping was somewhat greater at the slower tempo (15.1 ms) than at the faster tempo (13.5 ms), that of anti-phase tapping was slightly greater at the faster tempo (16.1 ms) than at the slower tempo (15.0 ms).

The mean relative asynchronies of the in-phase tapping condition are shown in Fig. 5. They closely replicate the results of Experiment 2 (Fig. 3). Again, the functions for the two tempi are more similar when plotted in terms of target–distractor separation (Fig. 5B) than when plotted in terms of relative phase (Fig. 5A), especially on the negative side. The correlation between the two functions is 0.47 (n.s.) in Fig. 5A, but (after linear interpolation) 0.84 (d.f. = 8, $p < 0.01$) in Fig. 5B. An ANOVA on these data showed a significant main effect of relative phase, $F(9, 54) = 8.3$, $p < 0.001$, $\varepsilon = 0.34$, which confirms the presence of distractor effects, and a significant interaction between relative phase and tempo, $F(9, 54) = 3.8$, $p < 0.04$, $\varepsilon = 0.29$, which reflects the misalignment of the functions of relative phase for the two tempi (Fig. 5A).

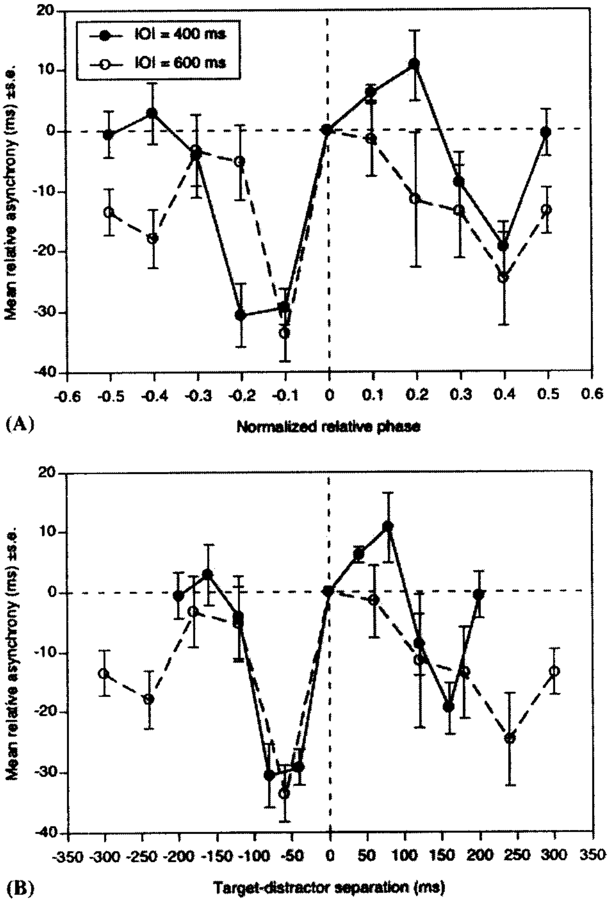

Fig. 5. Experiment 3: Average relative asynchrony of in-phase tapping for two sequence tempi (A) as a function of relative phase and (B) as a function of target–distractor separation.

Fig. 6 shows the mean standard deviations of the relative asynchronies, plotted in two different ways. These results, too, replicate the findings of Experiment 2 (Fig. 4). An ANOVA showed that variability was significantly greater at the slower tempo, $F(1, 6) = 71.2$, $p < 0.0001$, and varied significantly with relative phase, $F(9, 54) = 6.1$, $p < 0.003$, $\varepsilon = 0.39$. Moreover, the two-way interaction was significant, $F(9, 54) = 17.3$, $p < 0.04$, $\varepsilon = 0.42$, because the variation with relative phase was more pronounced at the slower tempo than at the faster tempo. The correlation of the two functions was 0.51 (n.s.) in Fig. 6A and 0.34 (n.s.) in Fig. 6B. Although this is hardly a significant difference, it runs counter to the perceptual integration hypothesis.

The results of the anti-phase tapping condition are shown in Fig. 7. These functions show significant similarities with the functions for the in-phase condition

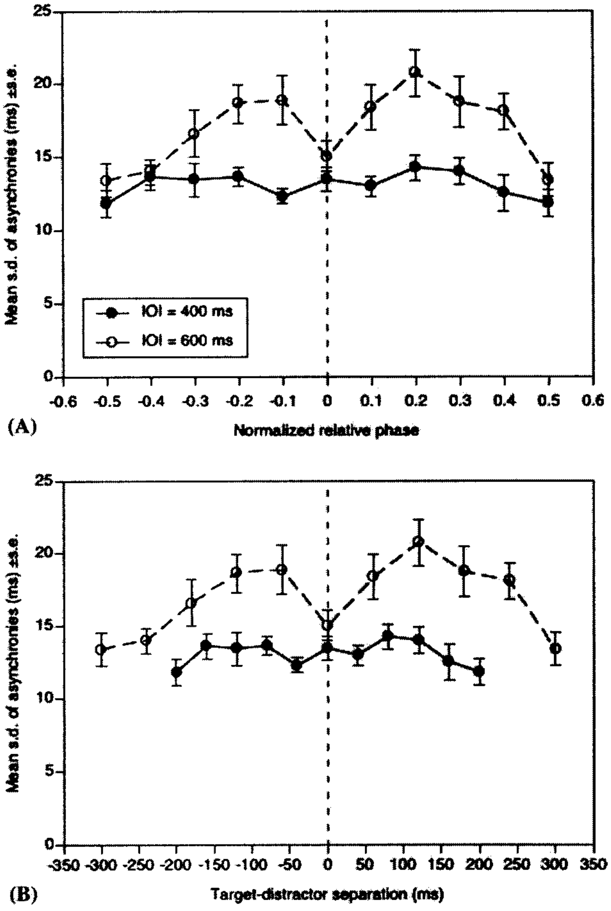

Fig. 6. Experiment 3: Average standard deviation of asynchronies of in-phase tapping for two sequence tempi (A) as a function of relative phase and (B) as a function of target–distractor separation.

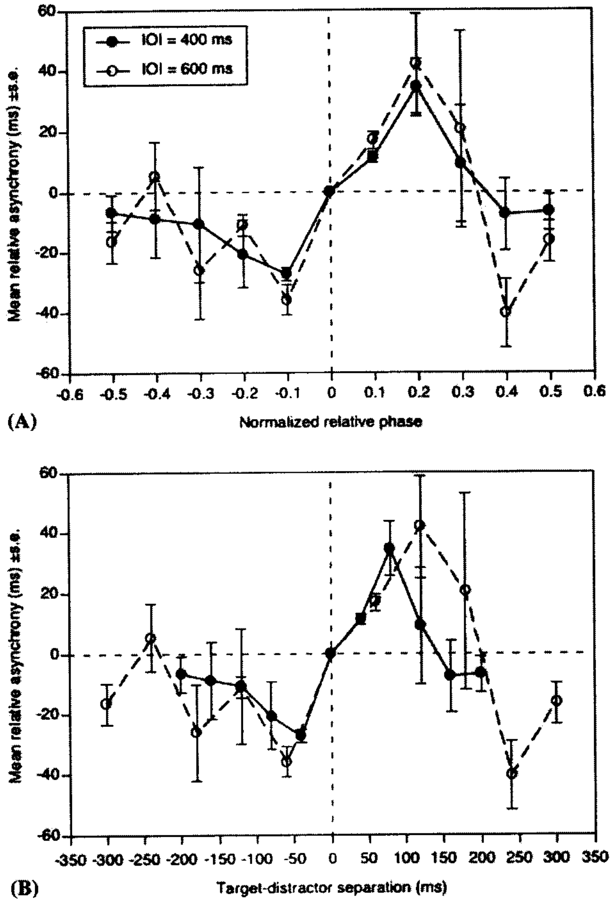

Fig. 7. Experiment 3: Average relative asynchrony of anti-phase tapping for two sequence tempi (A) as a function of relative phase and (B) as a function of target–distractor separation.

(Fig. 5). On the negative side, there is a dip of about the same depth (note the different y-axis scales in Figs. 5 and 7), although it seems to extend over a wider range than in in-phase tapping. On the positive side, a much larger distractor effect than for in-phase tapping can be seen, which may be attributed in part to the greater vulnerability of anti-phase tapping to distraction. Nevertheless, the pattern of results is basically the one predicted by the perceptual integration hypothesis. Two features of the function for the slow tempo – the dip at a relative phase of 0.4 and the local peak at a relative phase of −0.4 – suggest that attraction to close distractor tones (which were far from the target tones) did occur at the slow tempo. However, there was an unexplained dip at a relative phase of 0.4 in the in-phase data as well (Fig. 5), which cannot be attributed to attraction of taps to distractor tones.

An ANOVA revealed a significant main effect of relative phase, $F(9, 54) = 5.0$, $p < 0.02$, $\varepsilon = 0.29$, but no significant interaction between relative phase and tempo.

Unexpectedly, the two tempo functions seem better aligned in Fig. 7A than in Fig. 7B, at least on the positive side. However, the respective correlations, 0.85 (d.f. = 8, $p < 0.01$) and 0.72 ($p < 0.05$), do not differ greatly, and the positive distractor effects show large between-participant variability. Therefore, although these results do not provide further support for temporal separation as the controlling variable, they cannot be considered counter-evidence either.

In a combined ANOVA on the in-phase and anti-phase tapping data, with the additional variable of task, only the main effect of relative phase was significant, $F(9, 54) = 11.1$, $p < 0.001$, $\varepsilon = 0.34$. The Task × Relative Phase interaction was not significant, $F(9, 54) = 1.9$, $p < 0.19$, $\varepsilon = 0.26$, which confirms the relative similarity of the data in the two tasks.

Fig. 8 shows the mean standard deviations in the anti-phase tapping task. Like the corresponding functions in the in-phase tapping task (Fig. 6), they show minima at

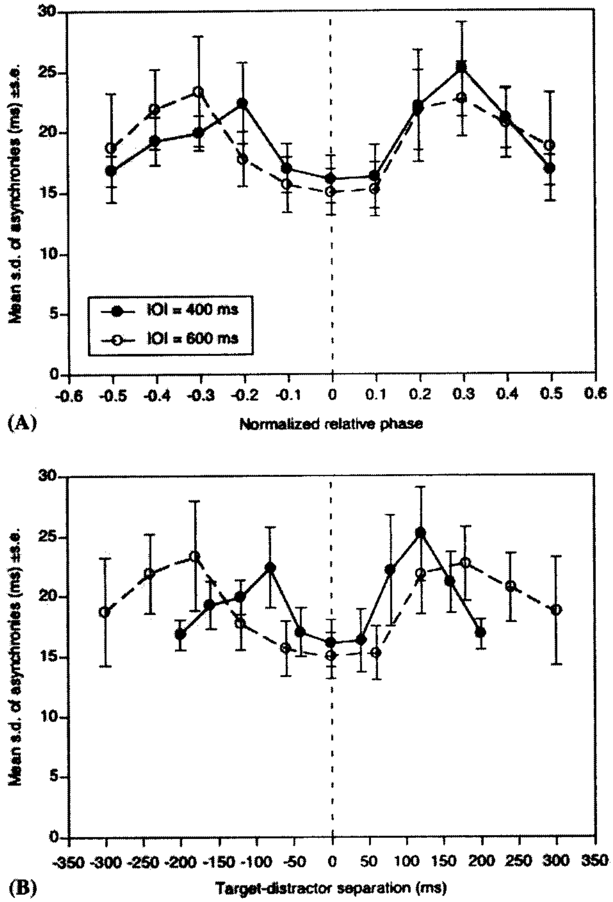

Fig. 8. Experiment 3: Average standard deviation of asynchronies of anti-phase tapping for two sequence tempi (A) as a function of relative phase and (B) as a function of target–distractor separation.

relative phases of 0 and ±0.5 (note that this refers to the relative phase of target and distractor sequences, not of taps and the target sequence) and peaks in between, but the peaks are farther removed from zero relative phase than they are in the in-phase tapping task, and they are equally present at both tempi. These differences may be due to the greater difficulty of the anti-phase tapping task, particularly at the faster tempo. Variability was similar at both tempi here, and an ANOVA revealed only a significant main effect of relative phase, $F(9, 54) = 7.0$, $p < 0.001$, $\varepsilon = 0.41$.

A combined ANOVA with the in-phase variability data showed, somewhat surprisingly, that the main effect of task was not significant, $F(1, 6) = 4.2$, $p < 0.09$, although the mean standard deviations were numerically greater in the anti-phase tapping task. In addition to the expected main effect of relative phase, $F(9, 54) = 8.8$, $p < 0.001$, $\varepsilon = 0.42$, there was a significant Task × Relative Phase interaction, $F(9, 54) = 4.7$, $p < 0.01$, $\varepsilon = 0.43$, which reflects the different location of the peaks in the respective functions. The main effect of tempo, $F(1, 6) = 11.2$, $p < 0.02$, and the Task × Tempo interaction, $F(1, 6) = 9.7$, $p < 0.03$, were also significant and reflect the presence of a tempo effect in the in-phase tapping task only.

Finally, a comparison of Fig. 8A and Fig. 8B reveals an unexpected fly in the ointment. This is the only clear instance in this study where the data for the two tempi are better aligned as functions of relative phase than as functions of temporal separation. The respective correlations are 0.69 (d.f. = 8, $p < 0.05$) and 0.25 (n.s.). This discrepant result remains unexplained for the time being. On the whole, the anti-phase tapping data support the hypothesis that the distractor effects derive primarily from perceptual integration of target and distractor tones. Some attraction to close distractor tones occurred at the slow tempo, but this does not contradict the perceptual integration hypothesis because target and distractor tones were too widely separated to be integrated in that case. However, the anti-phase tapping data do not support the hypothesis that the distractor effects are better characterized in terms of temporal separation than in terms of relative phase, and they differ from the in-phase tapping data in that respect.

5. General discussion

The results of this study replicate the distractor effect first demonstrated in Experiment 2 of Repp (2003a): Taps intended to be synchronized with target tones automatically shift in the direction of distractor tones, especially when the distractors precede the targets. The magnitude of this negative phase shift was smaller than in the original experiment, but it was reliable in all three experiments. Its temporal extent in terms of the absolute separation between distractor and target tones was similar to that in the original study: The results of Experiments 1 and 3 suggest a range of less than 120 ms, whereas those of Experiment 2 indicate a slightly wider range for both negative and positive phase attraction effects. These findings are consistent with the perceptual integration hypothesis, according to which successive tones falling within a temporal integration window of 100–150 ms duration are grouped together and jointly engage the phase correction process that helps maintain synchrony between the taps and the target sequence (Repp, 2003a).

It may not be a coincidence that the duration of this hypothetical integration window is of roughly the same magnitude as the shortest simple reaction times to auditory stimuli: If there is not enough time to act in response to a stimulus, that stimulus may form a functional unit with the next stimulus, even if only a single overt response (or none at all) is required. In other words, for a tone to be perceptually segregated from a subsequent tone, sufficient processing time to enable an action may be required. The same reasoning may explain why it is not possible to coordinate actions with single tones in a stream whose rate exceeds 8–10/s (Bartlett & Bartlett, 1959; Repp, 2003b) or to count tones accurately at such fast rates (Massaro, 1976; Taubman, 1950). Obligatory grouping may also explain the finding that an "attentional blink" in rapid serial presentation of auditory sequences can be elicited only at sequence rates of 8/s or faster (Arnell & Jolicoeur, 1999).

The in-phase tapping results of this study strongly suggest that the distractor effect is governed by the absolute temporal separation between target and distractor tones, not by their relative phase, just as the perceptual integration hypothesis predicts. The anti-phase tapping results of Experiment 3 are more ambiguous, however. Although the general pattern of the asynchrony data is more consistent with the perceptual integration hypothesis than with the alternative hypothesis of attraction to independent tones, it is neutral with regard to the absolute/relative time issue. Moreover, the pattern of variability actually seems to be governed by relative phase, not by absolute temporal separation. This result is difficult to reconcile with the other findings in this study, and further research will be necessary to explore its causes.

It is interesting that leading distractor tones have a stronger effect than lagging distractor tones in in-phase tapping. The direction of this asymmetry is contrary to Povel and Okkerman's (1981) finding that listeners tend to perceive the second tone in a group of two tones as accented. Recent experiments (Repp, in press a,b) have suggested that it is easier to synchronize with tones that are perceived as accented in cyclically repeated groups of two or three tones. In those experiments, the tones were identical, whereas here they differed in pitch. Could it be that in a group of two tones of different pitch, the first tone tends to be heard as accented? This seems unlikely but needs to be investigated. A more important difference is that the tone onsets in these other studies were usually separated by more than 120 ms. It may be that only when the two tones fall within the integration interval and form a really tight group that the first tone becomes dominant, because of onset-biased weighting within the integration window.

There was a pitch effect in Experiment 1 which replicated a tendency found in the earlier study of Repp (2003a): Low targets were more resistant to distractors than high targets, or conversely, low distractors exerted stronger phase attraction than high distractors. This is consistent with the finding of Handel and Lawson (1983) that people prefer to synchronize taps with the lower-pitch tones in polyrhythms. Curiously, however, Experiment 2 showed a pitch effect in the opposite direction. The reason for this is unclear. The magnitude of the pitch difference (3 semitones in Experiments 1 and 2 versus 8 semitones in Experiment 3) seemed to make little difference, just as in the earlier study.

In conclusion, whether absolute or relative time is used as a descriptor of periodic processes is often a matter of theoretical approach: Information-processing approaches favor absolute intervals, whereas dynamical systems approaches favor relative phase. However, it is basically an empirical issue whether any particular phenomenon is better described in terms of absolute or relative measures of time. Although actions that are controlled with reference to periodic external events can be modeled conveniently in terms of coupled oscillators and their relative phase, this does not rule out processing stages that are limited by absolute integration intervals. Such intervals may in turn reflect dynamic processes taking place at a faster time scale, such as gamma oscillations in the brain. The influence of a periodic distractor sequence on synchronization with a target sequence seems to reflect an absolute integration interval of 100–150 ms duration which fuses close target and distractor tones into single perceptual units.

Acknowledgments

This research was supported by NIH grant MH-51230. I am grateful to Susan Holleran for help with data analysis.

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