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ORIGINAL ARTICLE

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Tracking simple and complex sequences

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Abstract We address issues of synchronization to rhythms of musical complexity. In two experiments, synchronization to simple and more complex rhythmic sequences was investigated. Experiment 1 examined responses to phase and tempo perturbations within simple, structurally isochronous sequences, presented at different base rates. Experiment 2 investigated responses to similar perturbations embedded within more complex, metrically structured sequences; participants were explicitly instructed to synchronize at different metrical levels (i.e., tap at different rates to the same rhythmic patterns) on different trials. We found evidence that (1) the intrinsic tapping frequency adapts in response to temporal perturbations in both simple (isochronous) and complex (metrically structured) rhythms, (2) people can synchronize with unpredictable, metrically structured rhythms at different metrical levels, with qualitatively different patterns of synchronization seen at higher versus lower levels of metrical structure, and (3) synchronization at each tapping level reflects information from other metrical levels. The latter finding provides evidence for a dynamic and flexible internal representation of the sequence's metrical structure.

Introduction

The ability to coordinate motor behaviors with auditory stimuli has been widely studied (e.g. Bartlett & Bartlett, 1959; Dunlap, 1910; Fraisse, 1956; Kolers & Brewster, 1985; Michon, 1967; Stevens, 1886; Vos, Mates, & van Kruysbergen, 1995; Woodrow, 1932). Most studies have investigated synchronization to simple, structurally isochronous sequences, and have uncovered several robust behavioral phenomena. Various models have been proposed to account for these findings, which include rate dependence, anticipation bias, patterns of variability, compensation for phase perturbations, and learning (e.g. Chen, Ding, & Kelso, 1997; Hary & Moore, 1987; Kelso, DelColle, & Schöner, 1990; Mates, 1994a,b; Pressing & Jolley-Rogers, 1997; Semjen, Vorberg, & Schulze, 1998; Vorberg & Wing, 1996; Zanone & Kelso, 1992). As yet, however, such models have not been convincingly extended to more complex and naturalistic stimuli, such as music. Even the simplest musical performance presents considerably more complexity than the ticks of an auditory metronome. And while a great deal is known about synchronization with simple acoustic sequences, relatively little is known about how people accomplish the similar feat of synchronization with more complex auditory stimuli. It is this issue that motivates the current study.

How do we synchronize with musical rhythms? We begin with the observation that when we listen to music we hear a beat – a psychological, subjectively isochronous, pulse train – to which we can synchronize by tapping our foot, snapping our fingers, and so forth, reflecting a kind of motor equivalence in the temporal domain (Kelso, Fuchs, Holroyd, Lancaster, Cheyne, & Weinberg, 1998). The notion of synchronizing to the beat of the music is less straightforward than it might first appear, however, especially when one considers the temporal complexity of performed music. Except in the case of very simple music, it is rarely clear from an analysis of the acoustic signal where "the beat" is to be found, even though it may be quite obvious upon auditory presentation of the performance. Furthermore, musical rhythms are generally organized according to hierarchical, multi-periodicity metrical structures, such that beats are perceived at different time scales simultaneously (Lerdahl & Jackendoff, 1983; Yeston, 1976). It is widely accepted that listeners apprehend metrical structure in musical rhythms, and are able to choose from among them the particular beat level to control

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synchronization (e.g. Snyder & Krumhansl, 2000; Drake, Penel, & Bigand, 2000). Finally, performed musical rhythms often contain large, systematic fluctuations in tempo, known as 'rubato'. Rubato is not noise, rather it comprises patterned temporal gestures that communicate structural and emotional interpretations of the musical material (Epstein, 1995; for a review of musical performance timing, see Palmer, 1997). Perception of rubato requires the perception of deviations from the categorical durations, and, as a prerequisite, the categorization of performed durations, where categories are defined by the metrical structure (Clarke, 1987). Thus, communication of musical expression requires tempo tracking on the part of listeners (Large & Palmer, 2001).

The current study seeks to address issues of stimulus complexity by examining compensation for temporal stimulus perturbations in synchronization tapping. In two experiments, synchronization to simple and more complex rhythmic sequences was investigated. Experiment 1 examined responses to phase and tempo perturbations within simple, structurally isochronous sequences, presented at different base rates. Experiment 2 investigated responses to similar perturbations embedded within more complex, metrically structured sequences; participants were explicitly instructed to synchronize at different metrical levels (i.e., tap at different rates to the same rhythmic patterns) on different trials. We found evidence for a dynamic and flexible internal representation of the sequence's metrical structure, and for adaptation of intrinsic period in both simple and complex rhythmic sequences. Implications for models of synchronization to music are discussed.

Experiment 1: temporal perturbations in simple sequences

Most models of rhythmic coordination rely upon the notion of an intrinsic frequency that characterizes the periodicity of rhythmic behavior independently, to some extent, of the stimulus periodicity. Depending upon one's theoretical orientation, this is captured as a parameter that represents the eigenfrequency of an emergent oscillation (e.g. Kelso et al., 1990), or the natural period of an internal timekeeper mechanism (e.g. Vorberg & Wing, 1996). Perception-action coupling, or some form of error-correcting mechanism, adjusts the phase of the oscillation to maintain synchrony with the stimulus in the presence of noise in perceptual and/or motor systems (Kelso et al., 1990).

Few theoretical models, however, explicitly consider temporal stimulus fluctuations to be an important factor in synchronization. Thus, models of perception-action coordination have not yet embraced issues arising from consideration of such factors as tempo modulation of musical sequences. Nevertheless, mismatch between the natural frequency of an oscillation and the tempo of the stimulus sequence would naturally arise when synchronizing to a performed musical rhythm, and models that rely solely on mechanisms of phase adaptation make predictions about such cases. Most models predict that 1:1 phase lock cannot be maintained if tempo change is too great. In cases where phase-locking is maintained, when stimulus rate slows, taps are predicted to precede the stimulus; when rate increases, taps are predicted to follow the stimulus (e.g., Kelso et al., 1990; Vorberg & Wing, 1996).

Other models explicitly consider tempo changes in the stimulus. For example, Mates et. al. (1992) proposed a linear model of synchronization tapping that included both phase and period adaptation. The nonlinear model proposed by Engbert, Schefcfczyk, Krampe, Rosenblum, Kurths, and Kliegl (1997) to account for tempo-induced transition in polyrhythmic hand movements contains error correction terms for stabilizing the overall tempo as well as the individual taps. Large (Large & Jones, 1999; Large & Kolen; 1994), and McAuley (1995) have proposed nonlinear models that include period adaptation to tempo changes. The latter have been applied to rhythms of musical complexity (e.g. Large, 1996; Large & Palmer, 2001); however, they have not been used to model perception-action coordination per se. Instead, these have been advanced as models of meter perception and attention, capturing synchronization of internal rhythms to rhythmic stimuli. Such approaches have been used to successfully predict time discrimination in complex auditory patterns (e.g., Large & Jones, 1999; McAuley & Kidd, 1998), and perception of expression in music performance (Large & Palmer, 2001). In principle, however, these models also make predictions about perception-action coordination. Period adaptation models predict that (1) phase lock can often be maintained, even in response to large tempo changes, and (2) steady state behavior will relax back to its initial phase attractor after stimulus tempo changes (Mates et al., 1992; Large & Jones, 1999). Measures such as relaxation time can be used to characterize the return to steady state, and thus the stability of the overall system (e.g., Kelso, Ding, & Schöner, 1992).

The general issue to be addressed by Experiment 1 is whether synchronization behavior can be described in terms of phase adaptation alone, or whether it is necessary to consider adaptation of both phase and period. This can be tested by introducing phase and tempo perturbations into otherwise isochronous sequences, and observing the relaxation back to steady-state synchronization. If the steady state phase relationship between taps and stimulus events changes after a tempo perturbation, as predicted by phase adaptation models, phase entrainment alone is implicated. On the other hand, relaxation back to the initial phase relationship implies adaptation of intrinsic period. The pattern of relaxation itself also has general implications. There are two types of relaxation profiles that one may expect to observe. In one, a more-or-less gradual return to steady state is observed, in the other, overshoot and oscillations are seen in the relaxation process. Adaptation of phase alone favors a pattern of gradual relaxation from phase perturbations, while for tempo perturbations phase will not relax back to its initial attractor state. Adaptation of intrinsic period favors a pattern in which overshoot and oscillation may be seen in response to phase perturbations, while a more gradual relaxation back to the initial attractor state would be expected for tempo perturbations.

Methods

Participants

Six participants (three musicians, three non-musicians) took part in the study. All were right-handed.

Apparatus

Stimuli were tone sequences generated by a Kurzweil K2500RS sampling synthesizer, controlled by a custom designed Max/MSP (Version 3.6.2) program running on a 450 MHz Macintosh G3 computer. Stimulus sequences were constructed using brief duration (50 ms) sine tones. Participants were seated in an Industrial Acoustics sound isolation chamber, and auditory sequences were presented via Sennheiser HD250 headphones. Participants placed the forearm of their right hand on a custom designed armrest and tapped on a DrumKat DK10 MIDI drum pad. Subjects' taps were recorded with a resolution of ± 1 ms by the Max/MSP program.

Procedure

Stimuli were presented at three different base rates, with corresponding inter-onset intervals (IOIs) of 400, 600, and 800 ms. Six trials were presented at each base tapping rate. IOIs for an example trial with a base rate of 600 ms are shown in Fig. 1. Each trial began with a plateau of 16–24 cycles to allow participants to settle into a steady state. Following the initial plateau, six phase and six tempo perturbations, with magnitudes of ± 15%, ± 8%, and ± 3% of the base interval, and a 0% phase perturbation (baseline) were presented in random order in plateaus of 24–32 cycles. A phase perturbation was defined as a change to the single IOI at the beginning of a plateau, while a tempo perturbation was defined as a change to all of the IOIs within a plateau. Although there are other possible ways to perturb tempo, this method allowed the most straightforward measurement of relaxation time. To return participants to the base rate, tempo perturbations were followed by a 12–16 cycle plateau at the base IOI. Participants were instructed to synchronize their taps with the auditory sequence.

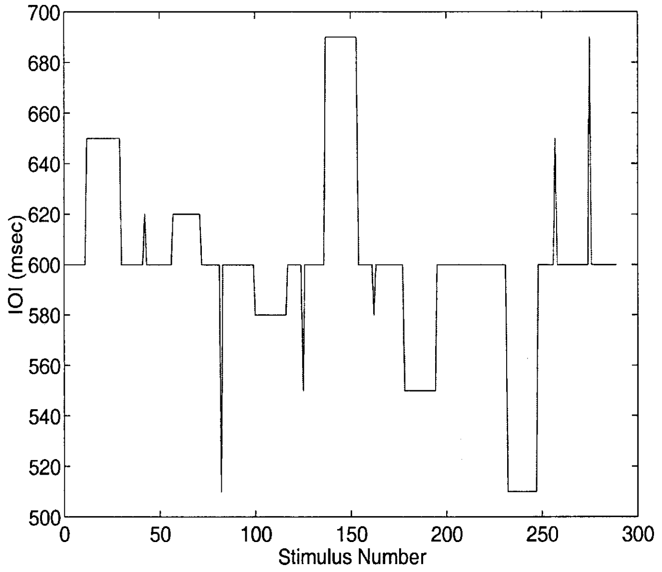


Fig. 1 IOI of the stimulus for a representative trial with a 600 ms baseline IOI

Analysis

Synchronization error was measured as the phase of each tap within the current stimulus cycle. Relative phase was chosen as a measure because it succinctly captures perception-action coordination, and has been shown to exhibit a well-defined dynamics (Kelso et al., 1990). Point estimates of relative phase (deGuzman & Kelso, 1991) between the stimulus and tap were obtained using the equation

$$\phi_n = \frac{T_n - S_n}{S_{n+1} - S_n}(\text{mod}_{-0.5,0.5}1) \tag{1}$$

where T_n is the time of tap n, S_n is the time of the closest stimulus event, and S_{n+1} is the time of the subsequent stimulus. Thus, relative phase was measured as a proportion of stimulus IOI, and restricted to the range $-0.5 \leq \phi_n < 0.5$. When the tap preceded the stimulus, relative phase was less than zero, $\phi_n < 0$, when the tap followed the stimulus, relative phase was greater than zero, $\phi_n > 0$. Relative phase values were averaged over individual trials, providing a time series of relative phase estimates for each subject, base rate, perturbation type (phase, tempo), perturbation direction (+/–), and perturbation magnitude (15%, 8%, 3%) for each of 12 cycles following the perturbation. The time series for the 0% phase perturbation was interpreted as the baseline measure of synchronization performance.

To facilitate measurement of whether tapping returned to baseline, we adjusted each time series for baseline performance by subtracting the baseline condition from the mean relative phase time series (i.e., from each of the six other time series at each base tempo). Thus, for these differenced time series, the value of zero corresponded to a mean relative phase equivalent to baseline performance. Next, each differenced time series was fit to the equation

$$\phi(n) = A\exp(-bn)\cos(2\pi fn + \theta) \tag{2}$$

where n is cycle number, and $\phi(n)$ is the relative phase on cycle n. The parameters A, b, f and θ, were fit using a Levenberg-Marquandt least squares procedure. This method is similar to that of Post, Peper, Daffertshorfer, and Beek (2000) and Post, Peper, and Beek (2000), who studied relaxation from mechanical perturbations during interlimb coordination. This equation can be accurately fit to relaxation curves that display either exponential decay or damped oscillations, both of which were observed in our data. The parameters b and f were of primary interest. The parameter b, $b > 0$, is related to the number of cycles required to return to baseline performance, or 'relaxation time', defined as $n_{rel} = 1/b$. The parameter f, $0 \leq f \leq 0.5$, described the frequency of any oscillation observed in the relaxation process, with non-oscillatory behavior (i.e., exponential decay) captured by the value $f = 0$. The parameter A reflected the size of the perturbation, and θ provided an extra degree of freedom to fine-tune the fits. To emphasize the first cycles of the plateau, where the majority of relaxation occurred, the first four cycles of each plateau were weighted more strongly than the remaining cycles.

Results

No significant effect of musical training was observed for any measures, so all participants were grouped together in subsequent analyses. Mean relative phase values for the baseline plateau (0% phase perturbation) are shown in Table 1 for the three tapping rates. No significant differences between the three sequence rates were observed.

Fig. 2 Relaxation curves (relative phase vs cycle number) averaged across all participants for phase and tempo perturbations with an (**a**) 400, (**b**) 600, and (**c**) 800 ms baseline. *Error bars* represent one standard deviation of the average across all participants at that cycle number. *Squares* indicate phase perturbations, *triangles* tempo perturbations. Tempo perturbations are characterized by a smooth, slow relaxation to baseline, while phase perturbations are characterized by faster relaxation with an overshoot of baseline on cycle numbers 2 or 3

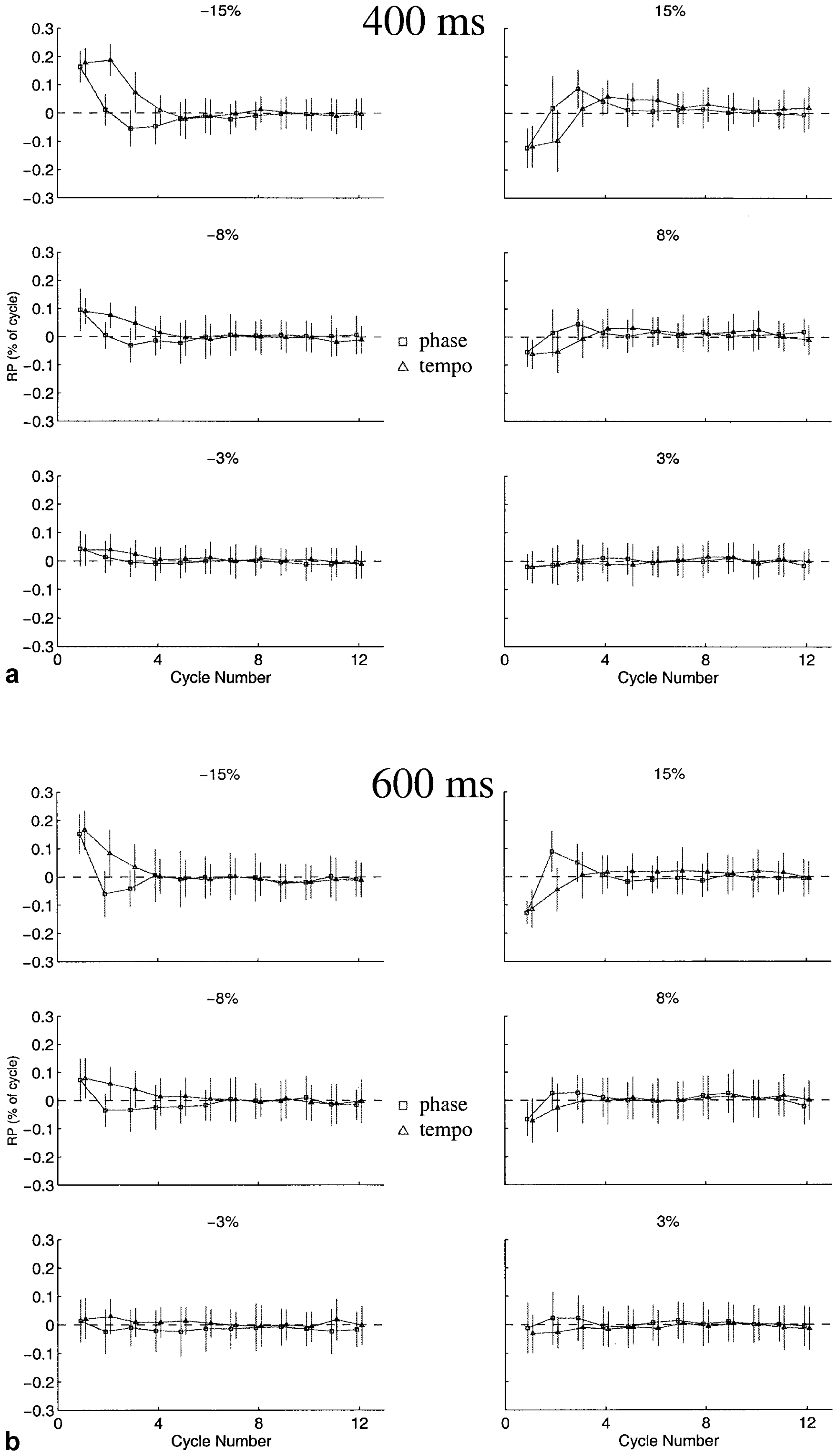


Fig. 2 (Contd.)

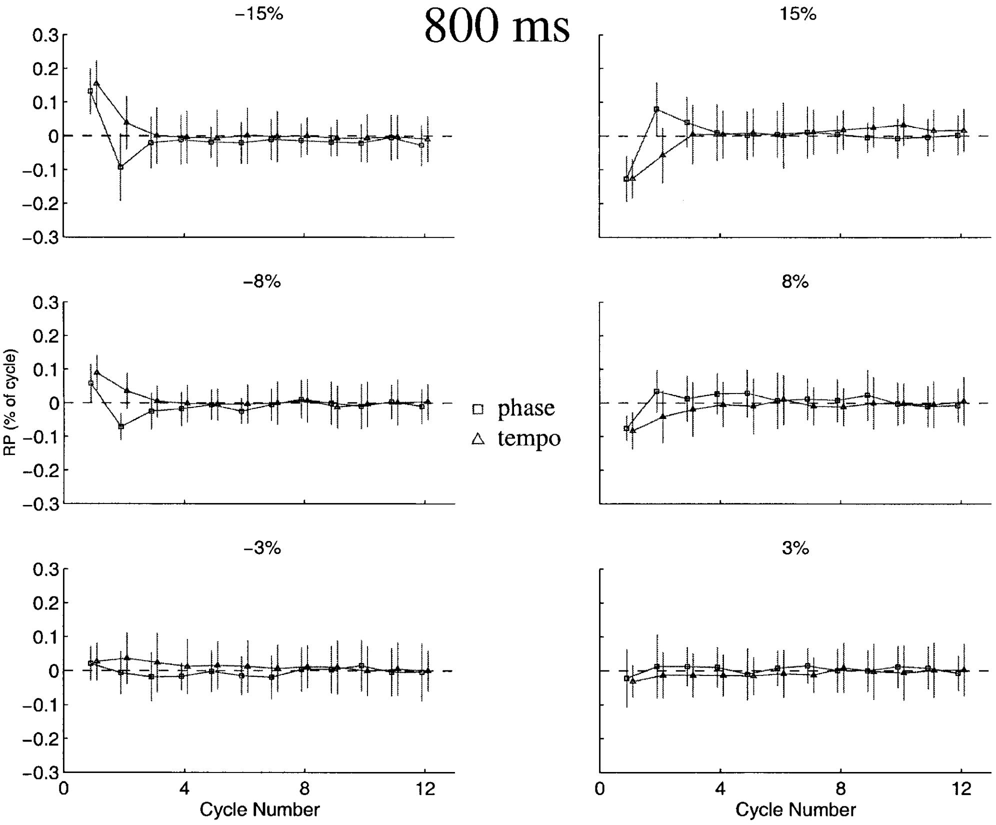


Table 1 Mean relative phase values for the three base tapping rates. All values are in normalized units

Tapping rate (ms)	Relative phase (std. dev.)
400	–0.0052 (0.0255)
600	–0.0090 (0.0468)
800	–0.0000 (0.0293)

Relaxation curves, averaged over trials and participants, are shown in Fig. 2 for phase and tempo perturbations for the 400 (a), 600 (b), and 800 (c) ms rate conditions. For the larger perturbations (± 15%, ± 8%) the initial relative phase was away from zero, but relaxed back to zero very quickly, usually within four cycles for all rates, perturbation types, directions, and magnitudes. The one exception was the + 15% tempo perturbation at the 400 ms rate. The manner in which relaxation occurred differed between phase and tempo perturbations. This can be seen in Fig. 3, which shows by cycle (collapsed across rate, perturbation type, direction, and magnitude) where relative phase was significantly different from zero (*t*-test, $P < 0.01$). Negative values indicate a change in the sign of relative phase from the initial perturbation, and thus denote overcorrection. Very few overcorrections are seen in the tempo perturbations; many overcorrections are seen for the phase perturbations. Tempo perturbations relaxed to zero smoothly and continuously. Phase perturbations, by contrast, typically overcorrected, resulting in a change of the sign of relative phase, before returning to baseline.

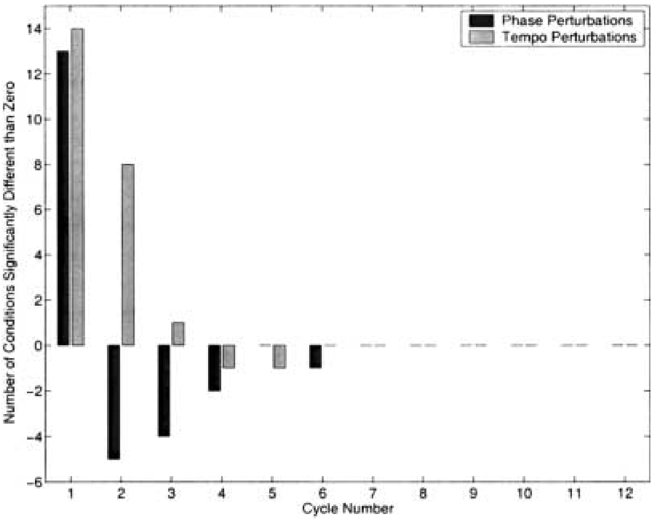


Fig. 3 Total number of conditions with relative phases significantly different than baseline (zero) for the data averaged across all participants and collapsed across perturbation sizes. A positive value indicates a significant difference in the same direction, while a negative value indicates a significant difference in the opposite direction, or an overcorrection. Overcorrections were more prevalent during phase perturbations

To understand the relaxation process in more detail, relaxation curves for each subject were fit to Equation 2. Fit quality was generally quite good, with fits accounting for over 50% of the variance in 89% of the conditions,

Table 2 Values of the *b* parameter fit to the data averaged across all subjects for Experiment 1

	400 ms		600 ms		800 ms	
	Phase	Tempo	Phase	Tempo	Phase	Tempo
–15%	0.52	0.76	6.36	1.09	9.53	0.87
15%	0.54	0.40	6.41	4.19	5.91	0.41
–8%	1.69	0.33	3.09	0.41	13.53	0.96
8%	13.87	0.25	6.50	3.50	6.88	0.70
–3%	0.41	0.93	3.09	6.17	4.21	0.32
3%	1.78	0.29	0.70	0.21	0.79	1.01

Table 3 Values of the *f* parameter fit to the data averaged across all subjects for Experiment 1

	400 ms		600 ms		800 ms	
	Phase	Tempo	Phase	Tempo	Phase	Tempo
–15%	0.09	0.12	0.19	0.05	0.24	0.08
15%	0.17	0.15	0.29	0.13	0.18	0.11
–8%	0.23	0.07	0.21	0.06	0.15	0.07
8%	0.23	0.11	0.15	0.19	0.18	0.17
–3%	0.16	0.06	0.21	0.06	0.15	0.07
3%	0.17	0.11	0.21	0.05	0.20	0.12

the exceptions being the ± 3% conditions. The two fitted parameters of interest, *b* and *f*, relating to relaxation time and oscillation frequency, respectively, were individually subjected to four-way repeated measures ANOVAs (3 rates × 2 perturbation types × 2 directions × 3 magnitudes). The fitted *b* showed a significant main effect of perturbation type, $F(1, 5) = 21.34$, $P < 0.01$, as shown in Table 2 (averaged over subjects). A larger value of *b*, $1/b = n_{rel}$(cycles), corresponds to faster relaxation, and was found for phase perturbations compared to tempo perturbations. A significant interaction of tapping rate and direction, $F(2, 10) = 4.89$, $P < 0.05$, was also found for *b*. The interaction arose from longer relaxation time for negative perturbations in the 400-ms rate condition. This longer relaxation process may reflect a reduced stability of the synchronized state at this faster tapping rate (i.e., critical slowing down, Kelso et al., 1990).

Values for the *f* parameter are shown in Table 3 (averaged over subjects). The ANOVA on the fitted *f* parameter revealed only a significant main effect of perturbation type, $F(1, 5) = 64.70$, $P < 0.0005$, with significantly greater *f* values for phase perturbations. Since a small value for *f* implies no oscillatory behavior, this test confirms what was shown in Fig. 3, namely that overshoots of baseline and oscillatory behavior occur more often and to a greater extent in response to phase perturbations than to tempo perturbations.

Discussion

The tapping phase relaxes to a steady state value equivalent to that of baseline performance in response to both phase and tempo perturbations. Qualitatively different relaxation profiles were observed for phase versus tempo perturbations. In response to phase perturbations, taps overshoot baseline, and the approach to steady state can be characterized as a damped oscillation. In response to tempo perturbations, relaxation displays a smooth, exponential profile. The existence of two qualitatively different relaxation patterns was reinforced by the strength of the fits of Equation 2 to individual subject data. In addition, the fits revealed faster relaxation from phase than from tempo perturbations. The lack of a significant effect of rate suggests that the relaxation process operates over stimulus cycles, not real time (i.e., intrinsic time, see Kelso & Tuller, 1987). Phase adaptation alone is insufficient to account for this pattern of results. Rather, the evidence suggests that intrinsic tapping frequency adapts to the changing local tempo of the stimulus. This agrees with the results of Thaut, Miller, and Schauer (1998) who provided evidence for the existence of period correction in the performance of a synchronization task similar to the one studied here.

Difference in tapping performance between musicians and non-musicians is sometimes reported in the literature (e.g., Drake et al., 2000), although there is no clear-cut evidence supporting the notion that musicians tap more accurately relative to non-musicians. In this task we found no differences in performance between musicians and non-musicians, suggesting that this natural response does not depend on training or skill. However, due to the small sample of participants serving in the two groups, any conclusion concerning the null effect must be interpreted with caution.

We found no differences in tapping asynchrony depending on rate. This observation is at odds with those of several experiments that have shown increasing

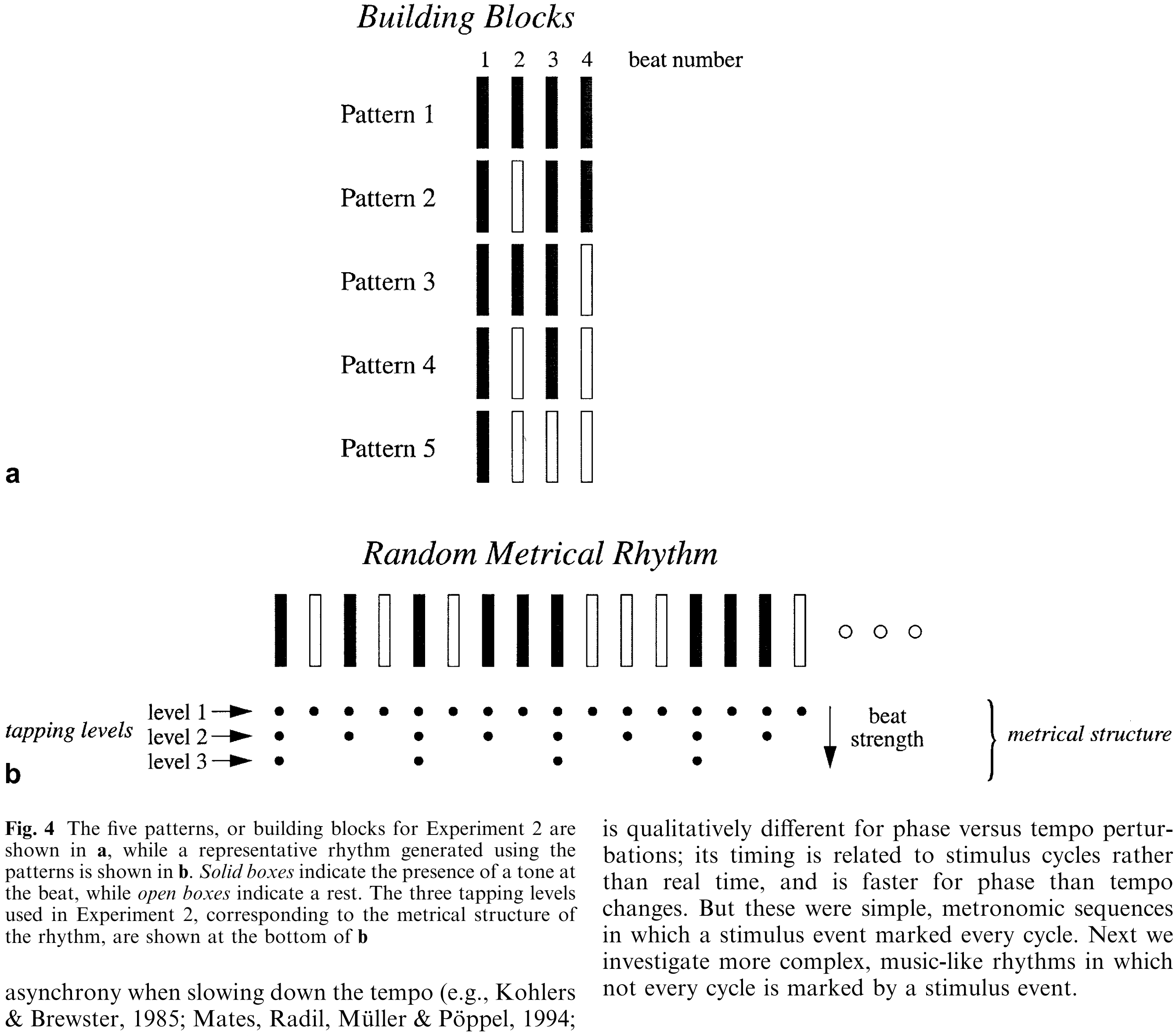


Fig. 4 The five patterns, or building blocks for Experiment 2 are shown in **a**, while a representative rhythm generated using the patterns is shown in **b**. *Solid boxes* indicate the presence of a tone at the beat, while *open boxes* indicate a rest. The three tapping levels used in Experiment 2, corresponding to the metrical structure of the rhythm, are shown at the bottom of **b**

asynchrony when slowing down the tempo (e.g., Kohlers & Brewster, 1985; Mates, Radil, Müller & Pöppel, 1994; Semjen, Schulze & Vorberg, 2000). Although these earlier studies measured raw asynchrony rather than relative phase, this difference alone cannot explain the discrepancy. Furthermore, we found no effects of perturbation size on the pattern of results. This finding appears at odds with that of Repp (2001), Thaut et al. (1998), and Thaut, Tian, and Azimi-Sadjadi (1998) who provided evidence that perturbations of different magnitudes are responded to differently. The main difference between the current study and the earlier investigations is the complexity of individual trials. In the current study participants were presented with perturbations of different directions, magnitudes, and types in each trial. Indeed, trials were designed to model the unpredictability of natural signals, and thus uncover more general synchronization strategies; thus, our design may have prevented optimization of response strategies that would be possible with more predictable stimuli.

In summary, participants adapt intrinsic tapping rate to match changes in local tempo. The relaxation process is qualitatively different for phase versus tempo perturbations; its timing is related to stimulus cycles rather than real time, and is faster for phase than tempo changes. But these were simple, metronomic sequences in which a stimulus event marked every cycle. Next we investigate more complex, music-like rhythms in which not every cycle is marked by a stimulus event.

Experiment 2: Temporal perturbations in metrically structured sequences

Experiment 2 investigated synchronization to metrically structured rhythms. Our hypothesis was that people can voluntarily synchronize at any salient metrical level, and can maintain synchrony in the face of temporal perturbations. To test this hypothesis we created stimulus rhythms that were at once random and metrically structured. The rhythms were constructed using five basic rhythmic patterns, shown in Fig. 4, termed ‘building blocks’. Each building block consisted of four event locations, termed ‘beats’. The time between beats was always 400 ms, but only some beats were marked by sounded events. This enabled creation of rhythms that were music-like in that they were composed of three different durations, 400 ms, 800 ms, and 1,600 ms, corresponding to musical eighth-, quarter-, and half-notes.

Table 4 Mean relative phase values for the three tapping levels and five patterns in Experiment 2. All values are in normalized units

	Pattern 1	Pattern 2	Pattern 3	Pattern 4	Pattern 5	Mean
Level 1	0.0143	0.0123	0.0081	0.0266	–0.0009	0.0121
Level 2	0.0239	0.0418	0.0162	0.0167	0.0448	0.0287
Level 3	0.0474	0.0039	0.0560	0.0155	0.0228	0.0291

Using this general scheme, it was possible to create 16 different building block patterns. To create a strong sense of metrical structure in these rhythms, however, we used only 5 of the 16 possible patterns, eliminating the empty pattern as well as all syncopated patterns. Musical syncopation is the occurrence of events on weak beats accompanied by the absence of events on strong beats (e.g., Cooper & Meyer, 1960). Thus, we retained only those patterns such that when events occurred on relatively weak beats, events also occurred on *all* stronger beats (within that pattern). We then randomly concatenated building blocks to create longer, random rhythmic sequences.

Patterns constructed in this way exhibited two properties that were important for this study. First, they unambiguously conveyed a sense of a binary metrical structure comprised of at least three levels. Second, they were random: the rhythmic sequence was never predictable, except in a statistical sense that conveyed metrical structure (Palmer & Krumhansl, 1990). The probability of an event on beat 1 was 1.0, on beat 3, 0.8 and on beats 2 or 4, 0.4. Thus, successful synchronization and recovery from perturbations required a general rhythmic competence, and could not be based upon memorization of a sequential rhythmic pattern.

Methods

Participants

Six participants (three musicians, three non-musicians) took part in the study. All were right handed. Two of the musicians and two of the non-musicians had participated in Experiment 1.

Apparatus

Same as Experiment 1.

Procedure

Stimuli consisted of five patterns, shown in Fig. 4, presented with a base interval of 400 ms between beats (termed the inter-beat interval, or IBI). Trials were presented in random order and began with one of the isochronous patterns (Pattern 1, 4, or 5) presented between 6 and 12 times; participants were instructed to synchronize tapping with the metronomic pattern to set the base tapping rate. Thus, participants began with a base tapping rate of 400, 800, or 1,600 ms (termed 'tapping levels 1, 2, and 3', respectively). Following the initial plateau, the five patterns were presented in random order for the remainder of the rhythm sequence. Each plateau began with a particular pattern (1–5) as well as with a particular perturbation (i.e., type, direction, magnitude). As in Experiment 1, six phase and six tempo perturbations, at –15%, –8%, –3%, 3%, 8%, and 15% of the base rate (400 ms), and a 0% phase perturbation (as a baseline) were applied to the stimulus in plateaus of 20–24 events. Also as in Experiment 1, phase perturbation was defined as a change in a single IBI (comparable to IOI in Experiment 1), while tempo perturbations were defined as a change to all the IBI's in the plateau. To return participants to the base tapping interval, tempo perturbations were followed by a 12–16 event plateau of random patterns at the base IBI. Trials were constructed so that each combination of tapping level, pattern, perturbation type, direction, and magnitude was repeated six times in the experiment. Participants were instructed to maintain the tapping level given at the beginning of the trial, and to synchronize with the stimulus.

Analysis

The data were analyzed as in Experiment 1 to find relative phases for each tap. For every tapping level, relative phase was calculated with respect to the local IBI (not the tapping rate). As in Experiment 1, the mean of the baseline condition was subtracted from the relative phase, and fits to Equation (2) were made using procedures identical to those of Experiment 1. *t*-tests ($P < 0.01$) were performed on the average relative phase at each event to assess significant differences from baseline and significant differences between tapping levels.

Results

Baseline tapping phase for the five patterns is shown in Table 4. A two way (3 tapping levels × 5 patterns) repeated measures ANOVA on baseline relative phase showed a significant interaction of tapping level and pattern, $F(8, 40) = 3.13$, $P < 0.01$; however there was no clear structure to this interaction. While the main effect of tapping level was not significant ($P = 0.19$), taps at levels 2 and 3 tended to be delayed relative to taps at level 1. Finally, baseline relative phase was nearly always positive, indicating that participants lagged behind the stimulus. This differed from baseline phase for Experiment 1, and a *t*-test comparing the 400 ms baseline from Experiment 1 with level 1 taps from Experiment 2 turned up a difference that approached significance, $t(10) = 1.66$, $P = 0.064$.

To illustrate some general behaviors that were apparent at tapping level 1, averaged relaxation curves for a single perturbation direction and magnitude, –8%, are shown in Fig. 5 for phase and tempo perturbations for all five patterns. Phase perturbations tended not to overshoot, but to relax smoothly back to baseline. For tempo perturbations, return to baseline began with an initial move in the opposite direction, and this behavior depended upon the pattern. For patterns 1 and 3, which had auditory tones at the first three events, the initial move away from baseline was small. For patterns 2 and 4, in which no auditory tone was present at event two, the move away from baseline was larger, before relaxing back to zero. Pattern 5 continued moving from baseline until another auditory event provided more information at the fifth beat. Similar relaxation profiles were found for other perturbation directions and magnitudes.

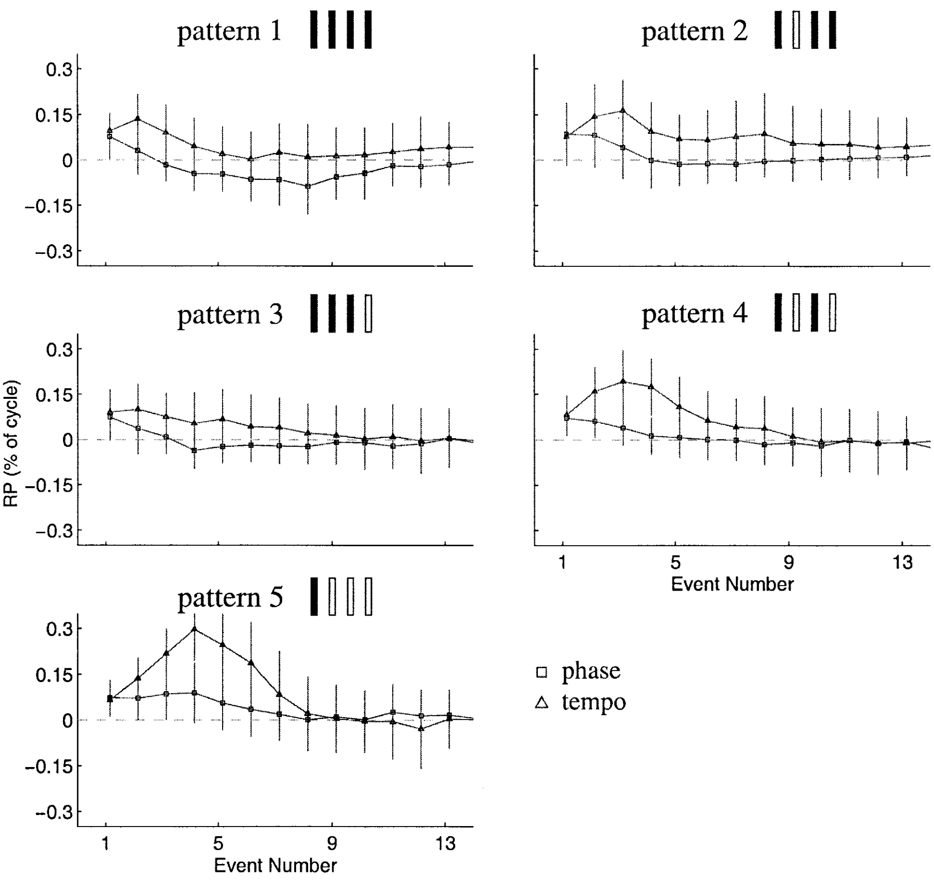


Fig. 5 Relaxation curves (relative phase vs cycle number) averaged across all participants for tapping level 1 for –8% phase (*squares*) and tempo (*triangles*) perturbations. *Error bars* represent one standard deviation of the average across all participants at that cycle number. Note that tempo perturbations are characterized by relative phases moving away from baseline in the first few events, while phase perturbations are characterized by a more continuous relaxation

The data from tapping level 1 was fit to Equation 2 (levels 2 and 3 were not fit to the model because few data points were available). An ANOVA on b revealed a significant main effect of perturbation type, $F(1, 5) = 22.23$, $P < 0.01$, and a significant interaction of perturbation type with perturbation direction, $F(1, 5) = 7.63$, $P < 0.01$. Faster relaxation times were found for phase perturbations than for tempo perturbations, and this difference was larger for perturbations in the positive direction, as shown in Fig. 6a. An ANOVA on f revealed no significant main effects, but turned up significant interactions of pattern with perturbation type, $F(4, 20) = 3.81$, $P < 0.05$, perturbation direction with perturbation size, $F(2, 10) = 8.50$, $P < 0.01$, and perturbation type with perturbation direction, $F(1, 5) = 8.01$, $P < 0.01$. Figure 6b shows the mean of fitted values of f as a function pattern and perturbation type (left) and as a function of perturbation type, direction, and size (right). These interactions reveal that the relaxation process exhibits a fine-grained structure that can be quite sensitive to the details of specific rhythmic situations. Further studies will be required to fully explore these subtle differences.

The values of f were lower overall in Experiment 2 than in Experiment 1, and the ANOVA on f showed a significant difference $F(1, 6) = 11.688$, $P < 0.025$, verifying that fewer overcorrections and oscillations occurred for the more complex sequences. Relaxation appeared slower in general for Experiment 2 versus Experiment 1; however, an ANOVA (2 experiments × 6 subjects nested within experiment × 2 perturbation types × 2 directions × 3 sizes) comparing b values between Experiments 1 (level 1) and 2 (400 ms condition) did not turn up a significant main effect.

Relaxation curves for tapping levels 2 and 3 for the –8% phase and tempo perturbations are shown in Fig. 7 for all five patterns. It is readily apparent that, compared to tapping level 1 (Fig. 5), the response to perturbations is very small, especially for tapping level 3. Most surprisingly, few disturbances are seen at the location of the perturbed event, and those that do appear are smaller than 8% of the cycle.

To further investigate relaxation behavior, we tallied the number of significant differences from baseline for all perturbation directions and sizes (Fig. 8a–e). When compared to Fig. 3 several features are apparent. First, this tally shows that tapping at level 1 did indeed take longer to relax to baseline than in Experiment 1. This observation was confirmed with a χ^2 test, which compared all data from Experiment 1, with level 1 data from Experiment 2, collapsed across all patterns. The comparison between Experiments 1 versus 2, and the number of significant differences from baseline (whether positive or negative) before versus after event 4 was highly significant, $\chi^2(1) = 21.51$, $P < .001$, indicating that the two variables were not independent. Thus, sequence

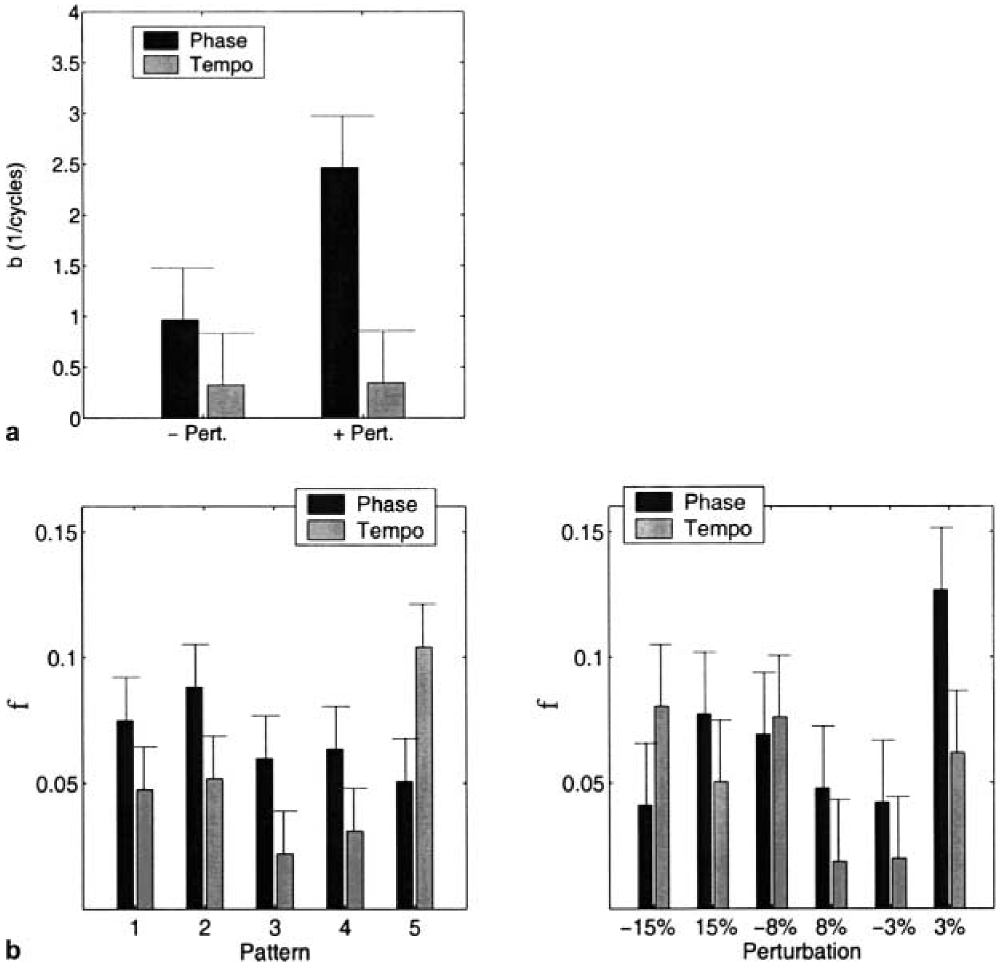


Fig. 6a, b Parameter fits for tapping level 1. **a** Mean value of *b* as a function of the direction of perturbation (positive or negative) and the type of perturbation (phase or tempo). **b** Mean values of *f* as a function of pattern (*left*) and perturbation size and direction (*right*). *Error bars* are one between subject standard error

complexity had an effect on the length of time during which significant differences were observed. The number of cycles required to reach baseline performance was greater for level 1 tapping that seen in Experiment 1, reflecting lower coordination stability for more complex sequences (Kelso et al., 1990).

Second, even when adjustment is made for the number of taps at each level, tapping levels 2 and 3 display fewer differences from baseline than observed at tapping level 1. Furthermore, different patterns display different relaxation profiles depending on tapping level. At level 1 some overshoots were tallied for patterns 1 and 3, but later in the plateau compared with Experiment 1. For levels 2 and 3, however, almost no overshoots were produced. In addition, although all patterns take longer to relax than Experiment 1, differences among patterns do not seem to reflect the number of missing stimulus events. For both phase and tempo perturbations, relaxation is fastest for patterns 2 and 4, and faster for pattern 5 than for pattern 3. Thus, stability of coordination does not appear to depend solely on the number of stimulus events. Most surprisingly, only 1 significant disturbance (out of a possible 60) was observed at the locus of a perturbation for tapping level 3, and only 14 at tapping level 2. By way of comparison, 41 significant disturbances were observed at the locus of a perturbation for tapping level 1. Moreover, at the tapping cycle following the perturbation, 16 (out of 60) significant disturbances were seen for level 3, and 26 for level 2. For tapping level 1, 39 significant disturbances were tallied. In other words, for tapping levels 2 and 3, disturbances were seen at the tapping cycle following the perturbation, not at the locus of the perturbation itself.

To further investigate differences between tapping behavior among the three metrical levels, we also tallied the number of significant differences between the relative phase of taps at levels 1 & 2, levels 1 & 3, and levels 2 & 3. These are shown in Fig. 9 for phase (a) and tempo (b) perturbations. Figure 9 reveals that significant differences among the relative phase of taps at different levels are rare, except at the locus of large perturbations (where tapping at levels 2 & 3 is undisturbed). By beat 5, differences between the taps of the three levels have mostly disappeared. Fewest differences are seen between levels 2 & 3, more differences between levels 1 & 2, and the most between levels 1 & 3. There are slightly more significant differences for tempo than for phase perturbations.

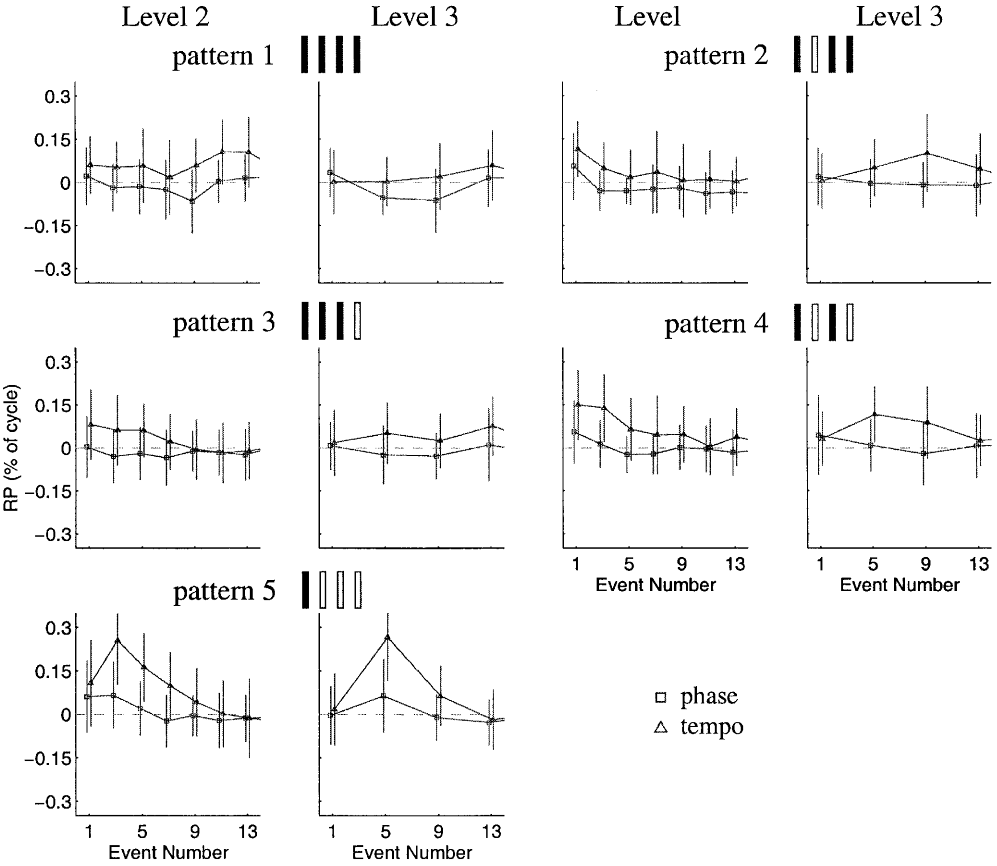


Fig. 7 Relaxation curves (relative phase vs cycle number) averaged across all participants for tapping levels 2 and 3 for 8% phase (*squares*) and tempo (*triangles*) perturbations. Error bars represent one standard deviation of the average across all participants at that cycle number. When compared with tapping level 1 (Fig. 5) relative phases are much closer to baseline

Discussion

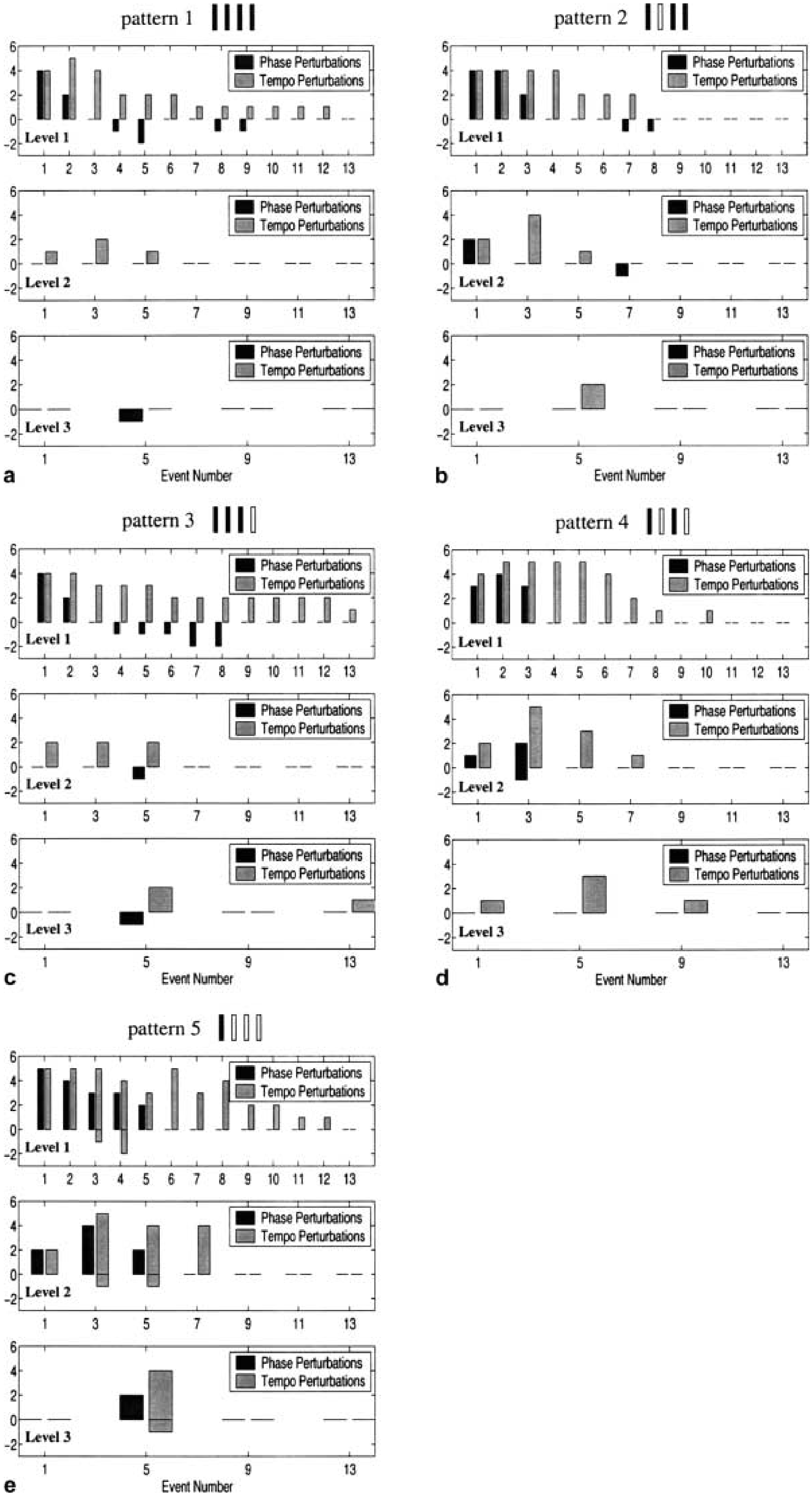
Experiment 2 demonstrated that people can synchronize to random, metrically structured rhythmic sequences. The unpredictability of the patterns rules out the possibility that coordination of action depended upon learning of specific rhythmic patterns (c.f. Pressing, 1999; Vorberg & Hambuch, 1984). Furthermore, successful recovery from phase and tempo perturbations in unpredictable rhythms disconfirms the hypothesis that temporal tracking is based solely upon prior learning of specific sequences of auditory events (cf. Cottrell, Nguyen, & Tsung, 1993). This basic finding points to a natural, inherently rhythmic faculty, that is not based on learning of specific event sequences, rhythmic patterns, or response strategies.

Participants were able to synchronize at any one of several salient metrical levels. For lower levels (1 & 2), taps sometimes marked subdivisions between sounded events, while for higher levels (2 & 3) sounded events sometimes subdivided the tapping interval. How is this behavioral flexibility to be explained? One possibility is that coordination at the three different levels reflects three distinct synchronization strategies. Another possibility is that this behavioral flexibility reflects the simultaneous representation of three periodicities within a single coordinative structure (Large, 2000; Large & Jones, 1999; Large & Palmer, 2001), similar to a music-theoretic metrical structure (e.g. Lerdahl & Jackendoff, 1983; Yeston, 1976). The findings of Experiment 2 favor the latter interpretation.

Significant synchronization disturbances were rarely seen at higher metrical levels. Those that were observed almost never occurred at the locus of the perturbation, and disturbances occurred most frequently on the tapping cycle following the perturbation. This phenomenon, in which the disturbance caused by a temporal perturbation is delayed by one response cycle, has been termed ‘next-cycle adaptation’ (Orlovskii & Shik, 1965; Kelso, Tuller, & Harris, 1983), and has been seen in other perturbation situations. For tempo perturbations, on some patterns, next-cycle adaptation may be explained by a lack of acoustic beat-markers, making perturbation type (phase vs. tempo) ambiguous. However, this explanation accounts for fewer than half of the relaxation patterns. It does not explain relaxation of level 3 for patterns 1, 2, 3, and 4, and it does not explain level 2 behavior for patterns 1 or 3. Additionally, the phase of taps was rarely different among the three metrical levels, except at the locus of large perturbations, where levels 2 and 3 were undisturbed.

Together these observations have two implications. First, covert monitoring of level 1 may have affected tapping at levels 2 & 3. At the higher levels, taps lagged slightly behind the stimulus events; and as a proportion of tapping cycle, perturbations are smaller at these levels

Fig. 8 Total number of conditions with relative phases significantly different than zero for the data averaged across all participants and collapsed across perturbation sizes for pattern 1 (**a**), pattern 2 (**b**), pattern 3 (**c**), pattern 4 (**d**), and pattern 5 (**e**). A positive value indicates a significant difference in the same direction, while a negative value indicates a significant difference in the opposite direction, or an overcorrection. As compared with Experiment 1 (Fig. 3) few overcorrections are seen, although once again they occur more frequently in phase perturbations



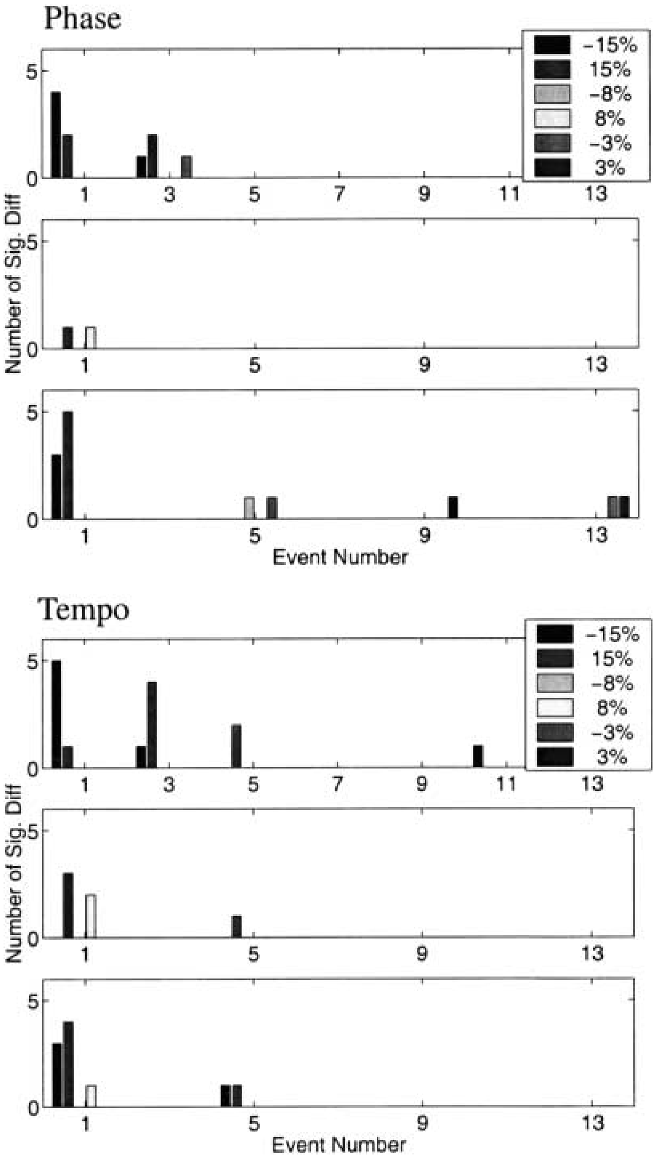


Fig. 9 Number of significant differences (out of a maximum of five) between tapping levels, collapsed across five patterns, for mean relative phases across all participants. Note that very few significant differences are present after event 3, and then usually only with the largest perturbations

(800 and 1,600 ms). Thus, it seems likely that disturbances were not observed because relaxation occurred immediately at the locus of the perturbation (within the 50 ms stimulus on-time of the displaced event). If lower levels of structure were also being monitored and had not fully relaxed, this would cause delayed phase disruption at higher levels, resulting in next-cycle adaptation.

Second, covert monitoring of levels 2 & 3 may have served to stabilize synchronization at level 1. Level 1's slow relaxation may be taken as an indication of very weak stimulus coupling, yet phase wrapping was never observed. Furthermore, level 2 & 3 taps were always better synchronized than level 1, while significant phase differences among levels virtually disappeared by beat 5. Perhaps stimulus coupling was stronger at levels 2 & 3, where stimulus events were more likely, even when overt tapping was at level 1. Thus, synchronization at level 1 may reflect coupling among internally monitored beat levels more than it reflects coupling between stimulus and taps. For these reasons, it seems likely that different levels of metrical structure were tracked simultaneously, and interacted with one another, and that their interaction was reflected in observed synchronization behavior.

General discussion

In response to temporal perturbations, intrinsic tapping period adapts to reflect the local tempo of rhythmic sequences. For metronomic sequences, relaxation times are fast and, in the case of phase perturbations, overcorrection is usually observed. In the case of tempo changes, relaxation is somewhat slower, and smooth relaxation curves are seen. More complex, metrically structured sequences also provide a viable stimulus for coordination. Participants can synchronize to unpredictable, metrical sequences at any prescribed metrical level, and they are able to produce taps corresponding to beats that may or may not be marked by a stimulus event on any given cycle. Taps are produced later for these more complex sequences. Wohlschläger (2000) has made a related observation in a synchronization tapping task: Insertion of random sounds between metronome clicks, a very different type of stimulus complexity, also eliminates negative asynchrony.

At the lowest metrical level, relaxation times are longer than observed for structurally isochronous sequences. At higher metrical levels, synchronization disturbances are rarely observed at the locus of a perturbation, and most often at the first tapping cycle following a perturbation. Taps at all metrical levels are produced at nearly the same phase (relative to baseline) by the fifth stimulus cycle. This provides a strong indication that synchronization need not always be based on a perceived asynchrony between a physical tap and a physical stimulus event. Rather, for complex rhythms, perceived beats – at multiple metrical levels – are synchronized with the stimulus and with each other.

Investigators in the field of music perception have proposed various theoretical and computational approaches to beat and meter perception in music (e.g. Brown, 1993; Dannenberg & Mont-Reynaud, 1987, Desain & Honing, 1991; Eck, 2000; Essens & Povel, 1985; Large & Kolen, 1994; Large 2000; Longuet-Higgins & Lee, 1982; Parncutt, 1994; Scheirer, 1998; Steedman, 1978; Todd, Lee, & O'Boyle, 1999; Toiviainen, 1998; Van Noorden & Moelants, 1999; Vos, Van Dijk, & Shomaker, 1994). These models, known variously as beat induction or beat tracking models, attempt to predict the period and phase of the psychological pulse series (the beat) of a complex acoustic stimulus on a moment-to-moment basis. Until recently, however, there has been a relative paucity of evidence to guide such endeavors.

The current study adds to the results of recent investigations that have studied tapping to music (Jones & Pfordresher, 1997; Repp, 1999a, 1999b; Scheirer, 1998; Snyder & Krumhansl, 2000; Van Noorden & Moelants, 1999) and the effects of stimulus complexity in tapping and time perception (e.g. Deutsch, 1983; Jones & Yee, 1997; Large & Jones, 1999; Peper, Beek, & Van Wieringen, 1995; Povel & Essens, 1985; Pressing, 1998, 1999). Most recently, Drake et al. (2000) investigated tapping to performed musical rhythms. While less accurate than tapping to a metronomic stimulus, both musicians and non-musicians are able to track beats in performed musical rhythms. Furthermore, temporal fluctuations of musical performance appear to enhance perception of metrical structure, reflected as a greater range of choices for tapping period.

The stimuli used in the current study were distinctly non-musical. We used isolated phase perturbations and abrupt tempo changes; we also used random (albeit metrically structured) rhythms. Nevertheless, these stimulus structures and fluctuations may be diagnostic of the mechanisms of temporal tracking for complex stimuli, as we have shown here. Specifically, we found evidence that temporal tracking is based upon apprehension of rhythmic structures that may be exploited in the absence of other musical regularities (contour, pitch harmony, etc.), or memory for specific sequences.

The fact that participants are able to successfully synchronize with unpredictable patterns at prescribed metrical rates suggests that they are able to recruit and synchronize oscillations corresponding to different metrical frequencies at will. These results point to a self-organized representation of temporal structure (e.g., Large, 2000), flexible enough to track temporal fluctuations (e.g. Large & Kolen, 1994; McAuley, 1995), and in which different levels interact in temporal tracking (Large & Jones, 1999; Large & Palmer, 2001). Furthermore, stability differences between tapping rates, and between phase and tempo perturbations are consistent with an intrinsic relationship between stimulus rate and coordination stability, as has been observed in previously (Kelso et al., 1990), but not incorporated in previous models of meter perception. These findings, along with the growing body of data on synchronization with musical rhythms may enable the development of models of musical synchronization that include tracking of isochronous rhythms as a special case.

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