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Musical synchronization

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The ability to coordinate rhythmic movement with rhythmic sound is fundamental to music performance and dance. This chapter begins by summarizing some of the most important findings about the synchronization of simple movements with simple rhythmic sequences, which constitutes the bulk of synchronization research. Three musical scenarios are then distinguished: (1) synchronization of simple movements with complex sequences (e.g. tapping to the beat of music), (2) synchronization of complex movements with a simple sequence (e.g. playing music with a metronome), and (3) synchronization of complex movements with a complex sequence (e.g. playing music in an ensemble). Research on each of these topics is reviewed, and possible future directions for research are considered.

Introduction

Sensorimotor synchronization (SMS), the coordination of rhythmic movement with rhythmic sensory stimuli, is a universal human skill that is fundamental to music and dance (Merker 1999–2000). Musical performance in a group requires the precise coordination of sound-producing movements with the sounds and movements produced by other musicians. Dance involves the coordination of (typically, quiet) movements with music and/or with the movements of other dancers. Some forms of dance, such as tap dancing and marching, also involve production of sound. Solo performers sometimes practice with a metronome, which is a form of SMS. Listeners to music and observers of dance may tap or sway along, and if so they are engaging in SMS.

Even if listeners are sitting still, their internal attentional rhythms may be entrained to the sensory input (Large and Jones 1999). Although this is an instance of synchronization and may even involve imaginary actions, it is not an instance of SMS because there is no overt movement. A solo pianist must coordinate the two hands and the fingers of each hand to achieve synchrony between a melody and its accompaniment, and between the tones of chords (Palmer 1996; Repp 1996). Although this involves both movement and sensory feedback, it is not an instance of SMS because there is no external rhythm that serves as a referent.

These examples delineate the subject matter of the present chapter, which is SMS in musical contexts. Most studies of SMS in the literature make no pretense of being concerned with music. They employ simple movements, typically finger tapping, and simple stimulus sequences, typically a metronome. Nevertheless, their results are relevant to music because they reveal the basic mechanisms underlying SMS. The next section summarizes the most important results of that research and gives selected references. (For a more detailed review and more complete references see Repp (2005c).)

Synchronization of simple movements with simple sequences

The mean negative asynchrony

One of the oldest findings in SMS research is that during tapping in synchrony with an auditory metronome the taps tend to precede the tones by a few tens of milliseconds (Miyake 1902). This is called the anticipation tendency or mean negative asynchrony (MNA). (An asynchrony is defined to be negative when the tap precedes the tone, positive otherwise.) It has been observed in nearly all simple SMS studies in the literature. Participants are generally unaware of this tendency. When they are trained by means of visual feedback to achieve a mean asynchrony close to zero, they feel they have to delay their taps in order to achieve this goal (Aschersleben 2003). Thus, the MNA corresponds to the subjective point of synchrony. In a classic study, Fraisse and Voillaume (1971) tricked unsuspecting participants in an SMS task by making the metronome tones contingent on their taps, thereby eliminating the MNA. The participants steadily accelerated their tapping tempo, as if trying to re-establish the MNA.

Many studies have been concerned specifically with the MNA because it seems to tell us something important about how perception and action are coordinated in time (see Aschersleben (2002) for a review). Various explanations for the MNA have been suggested, including different neural transmission times for different kinds of sensory information (Fraisse 1980), different central accumulation times for different amounts of sensory information (Aschersleben *et al.* 2004), an asymmetric cost function for asynchronies (Vos and Helsper 1992), minimization of variance through shortening of the internal tapping period (Vorberg and Wing 1996), and perceptual underestimation of empty intervals between tones (Wohlschläger and Koch 2000). Although each explanation has some merit, none of them seems to account for the full range of empirical findings.

Several of these findings suggest that the MNA is largely specific to simple SMS tasks and therefore not particularly relevant to musical SMS. First, the MNA decreases when auditory feedback (i.e. a tone) is made contingent on each

tap (Aschersleben and Prinz 1995), so that asynchronies can be gauged within the auditory modality. While such explicit auditory feedback is uncommon in SMS studies, it is the standard situation in music performance. In large part, the MNA seems to be a consequence of comparing auditory input with tactile and proprioceptive feedback from the movement. Second, the MNA tends to disappear when additional tones are inserted between the metronome tones or when additional movements intervene between taps (Wohlschläger and Koch 2000). This, too, occurs commonly in music, where rhythms are usually more complex than a simple beat. Third, musically trained individuals generally seem to show smaller MNAs than untrained individuals (Aschersleben 2002).

Nevertheless, the tendency to anticipate external referents may account for some phenomena observed in music performance, such as rushing when playing in an ensemble or coming in too soon after a rest.

Variability

Sensorimotor synchronization inevitably involves uncontrolled variability. Not only are movements inherently variable, but also the perception of a perfectly regular metronome is subject to variability arising in the neural circuitry. Wing and Kristofferson (1973) proposed an influential model according to which the variance of rhythmic movement has two additive components: one generated by a central timekeeper and the other contributed by more peripheral motor processes. Timekeeper variance increases with interval duration, whereas motor variance is relatively constant and thus makes less and less of a contribution to the total variance as the tempo decreases (Wing 1980). Perceptual variability likewise increases with interval duration and thus causes an increase in the perceptual threshold for changes in duration, which approximately follows Weber's law between about 300 and 2000 ms (Friberg and Sundberg 1995). Within these limits, a typical value for the coefficient of variation (the standard deviation as a percentage of the mean interval duration) of both movement timing and perception of timing is 4%, although musicians can show values less than half as large. The Wing–Kristofferson model was proposed to account for unpaced tapping, but it can easily be extended to SMS by adding error correction (see section on Error correction below).

Models of SMS typically assume variability to be random (i.e. white noise), but there is now strong evidence that biological noise does not have a flat spectrum but rather an increasing energy at low frequencies ($1/f$ or fractal noise; Gilden 2001). In unpaced tapping, this is reflected in fluctuations in tempo which occur at many time scales (Madison 2004). In SMS, such fluctuations in tempo are much smaller because of error correction with reference to the pacing sequence, but the asynchronies fluctuate in a similar manner (Chen *et al.* 1997,

2002). This is believed to reflect the workings of a complex dynamic system underlying performance.

Rate limits

Sensorimotor synchronization has both upper and lower rate limits, which roughly correspond to the interval durations beyond which Weber's law does not hold and may indeed be a consequence of a rapid increase in relative variability. The slowest rate at which SMS is possible corresponds to interval durations of about 2 s (Mates *et al.* 1994; Engström *et al.* 1996). At intervals longer than 2 s it becomes difficult to anticipate future events, and taps tend to follow rather than precede metronome tones. It is likely that this limit can be extended somewhat by mental subdivision strategies, such as musicians are likely to employ, but this has not yet been investigated.

The fastest rate at which synchronization with a metronome is possible depends strongly on the manner of synchronization. At least three different rate limits can be distinguished. When the task is to make one tap with each tone, the rate limit is set simply by the fastest rate at which the finger can move, which corresponds to inter-tap intervals of 150–200 ms for most people (Peters 1980). An even faster limit is evident when the task is to tap only with selected metronome tones, such as every fourth tone (Repp 2003) or only a single tone (Bartlett and Bartlett 1959), so that the biomechanical limit is avoided. In that case, synchronization is possible up to interval durations of 100–125 ms between tones. The eventual breakdown in coordination (which is evident as phase drift) suggests that the tones can no longer be attended to as individual events at such fast rates. A much slower limit is obtained when the task is off-beat (anti-phase) tapping, that is to tap at the midpoints of the intervals between tones. That limit is typically near interval durations of 350 ms (Repp 2005*a, b*). These values are for musically trained individuals; musically untrained participants may show considerably higher values.

The greater difficulty of anti-phase than in-phase coordination has been of particular interest to researchers who take a dynamic systems approach to SMS (e.g., Kelso *et al.* 1990). Their research usually focuses on continuous oscillatory limb movement, not on tapping. When the tempo is increased, a phase transition from anti-phase to in-phase coordination is commonly observed, which reflects a difference in the relative stability of these coordination modes. This difference is only evident when the system is stressed, however. Anti-phase tapping with a metronome tends to be *less* variable than in-phase tapping when the interval duration exceeds 400 ms (Semjen *et al.* 1992) because the taps subdivide the intervals, and shorter intervals afford lower variability as long as they exceed 200 ms (Repp 2003).

Empirical findings such as the ones reviewed here support London's (2002, 2004) contention that 200 ms is about the shortest possible interval between beats in music (cf. van Noorden and Moelants 1999), whereas 100 ms is the shortest possible interval between subdivisions of a beat.

Error correction

Sensorimotor synchronization cannot be achieved and sustained without error correction. Error correction prevents the inherent variability of the movement from having a cumulative effect on the times of occurrence of successive actions (Vorberg and Wing 1996). Two distinct error correction processes have been hypothesized to exist: phase correction and period correction (Mates 1994). Phase correction adjusts the time of occurrence of each successive action but does not affect the period of the underlying timekeeper or oscillator that governs the rate of the action. Period correction adjusts the interval of the timekeeper or period of the oscillator. A conceptual parallel can be seen between the two sources of variability postulated by the Wing–Kristofferson model and the two forms of error correction: In each case, a more central process and a more peripheral process are distinguished.

Both error correction processes occur against a background of uncontrolled variability, so that they cannot be observed easily in raw data. Two general approaches have been taken to investigate error correction: mathematical modelling and perturbation methods. The first approach estimates error correction parameters from raw time-series data (asynchronies and/or inter-tap intervals), whereas the second approach manipulates the timing of the pacing sequence and averages data across repeated trials in which the same timing perturbation occurs, thereby reducing the noise in the data.

Each error correction process is assumed to be based on sensory information about the temporal relationship between the taps and the pacing sequence. Phase correction is usually assumed to be based on perception of asynchronies. A linear phase correction model (Mates 1994; Pressing 1998; Vorberg and Schulze 2002) assumes that each tap is adjusted by a fixed proportion of the asynchrony generated by the preceding tap. This model has been quite successful in accounting for synchronization with a metronome, where there is little reason for period correction to occur. Period correction is assumed to be based on perception of a mismatch between the period of the internal timekeeper and the intervals of the pacing sequence, and the correction is assumed to be a linear function of that mismatch (Mates 1994). There are alternative ways of conceptualizing the perceptual information on which phase and period corrections are based, but discussion of this issue would lead too far here (see Hary and Moore 1985,
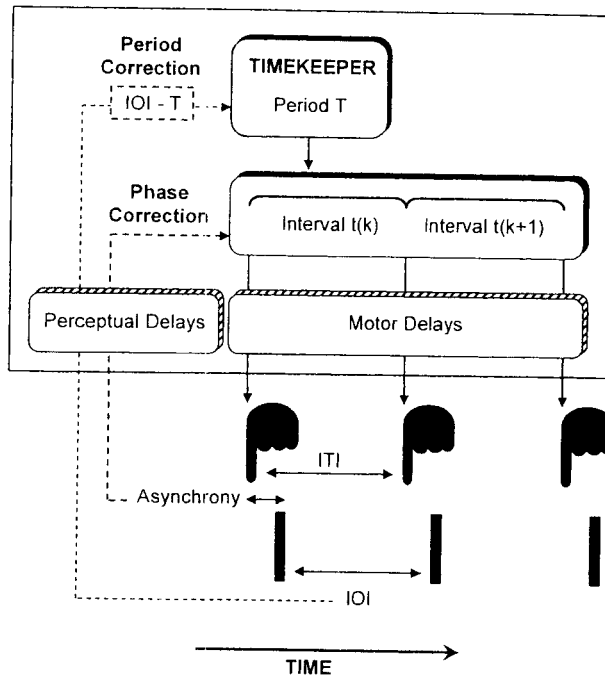
Fig. 4.1 Schematic diagram of the two-process error correction model for sensorimotor synchronization (after Mates 1994). A central timekeeper with period T is assumed to control the intervals $[t(k), t(k+1), ...]$ between successive motor commands. The period T can be adjusted on the basis of perceived discrepancies between its duration and the tone inter-onset interval (IOI) in the sequence (*period correction*). The intervals $[t(k), t(k+1), ...]$ can further be adjusted individually on the basis of registered asynchronies between taps and tones (*phase correction*). The frame indicates internal processes; only inter-tap intervals (ITIs) and asynchronies are directly observable. They are affected by both period correction and phase correction. (From Repp and Keller 2004.) Reproduced with permission of The Experimental Psychology Society (http://www.psypress.co.uk/journals.asp)

1987; Repp 2005c). The dual-process model of error correction is illustrated schematically in Fig. 4.1.

Phase correction and period correction are hypothetical *internal* processes that affect the observable behaviour, namely the adaptation of the relative tapping phase (asynchronies) and tapping period (inter-tap intervals) to the pacing sequence. Each internal process affects *both* observable variables (Repp 2001*b*), and therefore the processes are difficult to separate when they occur in tandem. For that reason, statistical models have focused mainly on phase correction in SMS with a metronome, where period correction can be assumed to be minimal. Timing perturbations in the pacing sequence, however, may elicit both phase and period correction, most obviously when the perturbation is a persistent tempo change. An estimate of period correction may be obtained by stopping the pacing sequence at various points and asking participants to continue tapping at what they consider the final tempo (Repp and Keller 2004).

The period of continuation tapping provides a retrospective estimate of the period of the internal timekeeper at the point where synchronization changed to self-paced tapping.

There is a good deal of evidence that phase correction is relatively automatic whereas period correction is in large part consciously controlled. Phase correction is the process that maintains synchrony with a metronome, but people are rarely aware of the continuous corrective adjustments they are making. When a phase perturbation is introduced in the metronome sequence, phase correction occurs in response to the perturbation regardless of whether or not the perturbation itself or the resulting asynchrony is detectable (Repp 2000, 2001a). In fact, phase correction seems to be most effective in response to small perturbations. Phase correction is also unaffected by diversion of attention (Repp and Keller 2004). When participants are instructed not to react to a detectable perturbation, they can reduce their phase correction response but are unable to suppress it completely (Repp 2002a; Repp and Keller 2004). By contrast, period correction in response to a tempo change in the pacing sequence is more effective when the tempo change is detectable than when it is not (Repp 2001b), is affected negatively by diversion of attention, and can be suppressed voluntarily (Repp and Keller 2004). Thus, whereas phase correction is a relatively low-level process that serves to stabilize SMS, period correction is a higher-level strategic process that may be involved not only in SMS but in other activities that require modulation of an internal period, such as expressive timing in music performance. Most likely, phase correction and period correction also engage different neural networks (Stephan *et al.* 2002; Praamstra *et al.* 2004), although much more needs to be learned about their neural underpinnings. A reasonable hypothesis based on existing data is that phase correction involves the cerebellum whereas period correction involves a corticothalamic circuit.

We are now ready to consider studies of SMS in situations that are somewhat closer to music performance. The next three sections divide these studies into three groups, according to the relative complexity of the pacing sequence and/or the motor activity. We first review studies of simple tapping to complex rhythms (i.e. more complex than a metronome) or to music. Then we discuss the performance of complex rhythms or of music in synchrony with a metronome. Finally, we consider tasks in which both the motor activity and the pacing sequence are complex, as they are in performance in a musical ensemble.

Synchronization of simple movements with complex sequences

Tapping a beat

One of the most commonly observed forms of spontaneous SMS is tapping a foot to the beat of music. Not surprisingly, therefore, isochronous tapping is frequently

used as a way of determining the period and phase of perceived metrical beat(s) in rhythmic patterns or in music (e.g. Oshinsky and Handel 1978; Handel and Oshinsky 1981; Handel and Lawson 1983; Parncutt 1994; Jones and Pfordresher 1997; van Noorden and Moelants 1999; Drake *et al.* 2000). However, these *beat-finding* studies are usually concerned only with the approximate position of the taps, not with asynchronies, variability, or error correction. Their main goal is not to study SMS but simply to locate the beat in the rhythmic structure, and often also to compare human performance with that of a computer algorithm. A few recent studies, however, have looked at synchronization with a beat in some detail.

Snyder and Krumhansl (2001) required participants to tap to the beat of piano ragtime music which was played under computer control with metronomic timing and equalized tone amplitudes. The sequences presented were either the original musical excerpts or only the highly syncopated right-hand part of the piano score, and each version was also reduced to a monotone pitch. The pitch manipulation had no effect on synchronization, but variability was greater when participants tapped with the right-hand part alone than when they tapped with the combined left- and right-hand parts. There was no significant MNA, which is consistent with the finding of Wohlschläger and Koch (2000) that tones interpolated between beats eliminate the MNA.

Large (2000) modelled the Snyder and Krumhansl data successfully with a computer algorithm based on a network of coupled oscillators. The oscillators were coupled not only to each other but also to the auditory input (by means of a coupling function in the model), and this resulted in the entrainment of an appropriate oscillator to the beat. Coupling to input is a dynamic systems implementation of phase correction (cf. Pressing 1999). Period correction was not included in Large's model; instead, a large number of oscillators with fixed frequencies were employed, so that switching between oscillators with similar periods was equivalent to period correction.

Toiviainen and Snyder (2003) conducted a beat tapping study in which excerpts from pieces by J. S. Bach in 4/4 meter were presented in three versions: integral, left hand only, or right hand only. Some excerpts started on a downbeat, whereas others started on the second beat. Again, no MNA was found; in fact, the taps lagged slightly behind the beat. Tapping variability was slightly greater for the separate parts than for the integral version, and slightly greater when participants tapped on the third beat of each bar than when they tapped on the first beat (the nominal downbeat). Whether participants tapped on the first beat or on the third beat depended in large part on whether the excerpt started on a downbeat or on the second beat; in the latter case, the second beat was usually interpreted as an upbeat (i.e. as the fourth beat in the measure).

A recent study by Patel *et al.* (2005) was not concerned with beat finding but with tapping variability as a function of metrical structure when the period and

phase of the beat were prescribed. Strongly metrical (SM) and weakly metrical (WM) rhythms were constructed by concatenating monotone sequences used previously by Povel and Essens (1985). Povel and Essens had shown that SM rhythms induce the feeling of a strong beat, whereas in WM rhythms a beat is more difficult to perceive. The main structural difference between the two is that SM sequences have events in every beat location, whereas in WM sequences some beat events are missing. Patel *et al.* prefixed each type of sequence with an isochronous induction sequence marking the beat period. Participants started tapping with the induction sequence and continued tapping the beat after the rhythmic pattern started. The results showed that taps were significantly more variable in WM than in SM sequences.

Several other conditions were included in that study. In one condition, participants simply tapped with an isochronous sequence of beats. Variability in that condition was similar to that of tapping with SM sequences. Thus, the variously subdivided beats of the SM sequences did not stabilize tapping any more than did a simple sequence of beats. However, tapping was less variable when participants tapped with every other tone of an isochronous sequence that was twice as fast. Thus, simple regular subdivision did improve the precision of SMS (cf. Repp 2003). In another condition, participants tapped with a sequence that had been generated from an isochronous beat sequence by deleting the beats that corresponded to missing beats in the WM sequences. Taps were more variable in that condition than in tapping with an isochronous sequence of beats, which suggests that the greater variability of tapping with WM sequences than with SM sequences was due to the absence of a number of beat events in the WM sequences. Indeed, when—in yet another condition—the missing beats in WM sequences were filled in, the tapping results were just like those with SM sequences because the manipulation had turned the WM into SM sequences. The importance of beat events can be understood by considering that taps falling on empty beats do not generate any error feedback (i.e. no asynchrony). Therefore, there is no phase correction following such taps (cf. Repp 2002c), and this increases the variability of the subsequent tap and thereby increases the overall variability of the asynchronies.

Similarly, when a tone occurs without an accompanying tap—a likely occurrence in tapping to the beat of a complex rhythm—there is no asynchrony at that point. Nevertheless, such subdivision tones are monitored perceptually and do affect phase correction (Large *et al.* 2002). Intervening subdivision tones reduce the phase correction response to a perturbation of the beat, and they elicit a shift of the next tap when their own timing is perturbed (Repp 2002d). Thus, additional structure in a pacing sequence (which could be music) is readily used for guiding simple movements, but additional movements (which could be those of music making) do not necessarily help synchronization with a simple beat

(although they do reduce the MNA in non-musicians, as Wohlschläger and Koch (2000) have shown). The latter situation requires more detailed study, however.

On-beat versus off-beat tapping with rhythms

The task in beat tapping studies is generally to tap in phase with the perceived beat, although occasionally participants may prefer to tap in anti-phase. In music performance, however, various other forms of coordination can occur, such as playing a note on the second and/or third beats of a rhythm in 3/4 meter, or on the second and/or fourth beats of a rhythm in 4/4 meter. Such tasks have been investigated only very recently in the laboratory (Repp 2005 *a*, *b*).

In these studies, simple monotone rhythms were presented, consisting of cyclically repeated groups of two or three tones, with the between-group interval being twice as long as the within-group interval(s). Participants were asked to tap with a particular tone in each cycle or in the middle of the 'gap' (i.e. the long interval). In several experiments, the dependent variable was the fastest tempo at which synchrony could be maintained. The results showed that it was easier to tap with a group-initial or group-final tone (which, according to Povel and Essens (1985) carry a rhythmic grouping accent and therefore are likely carriers of the metrical beat) than with a group-medial tone or in a gap. When one of the tones was accentuated by means of higher intensity and pitch, it was easier to tap with that tone than with other tones. When the (musically trained) participants were instructed to intentionally 'hear' the metrical beat on a particular tone while tapping in various positions, this dissociation of the metrical beat from the taps had surprisingly little effect on task difficulty as measured by the rate limit of SMS. In other words, participants found it just as easy to tap off the beat as on the beat, as long as they were tapping in the same group position. However, participants found it quite difficult to dissociate the metrical beat from their taps at fast tempi. To facilitate this dissociation, another experiment used slower tempi and focused on the variability of the asynchronies. Metrical interpretation still had no effect. Surprisingly, however, the effect of accentuation also went away, and the effect of grouping accent changed as well. Clearly, further research along these lines is needed, as the pattern of results is more complicated than expected.

Tapping to slow music: effects of musical structure

In the research considered so far in this section, the number of tones in the rhythm typically exceeded the number of taps made. In other words, the beats were subdivided in various ways. Several studies have investigated instead tapping in synchrony with the lowest metrical level of very slow music, so that there were few or no subdivisions between the tones that served as synchronization targets. This is

like tapping with a metronome, except that the pacing sequence is real piano music. The question of interest is whether and how the musical structure (melody, harmony, meter, perhaps even expressive features) affects the timing of the taps.

Repp (1999a, b) asked participants to tap along with the sixteenth notes in the first few measures of Chopin's Etude in E major, a very slow piece. The music was performed metronomically under computer control. Interestingly, the asynchronies and inter-tap intervals, when averaged across a number of trials and participants, exhibited a systematic timing pattern, even though the music was in strict time. Thus it appears that some aspects of musical structure have an involuntary influence on the precise timing of coordinated movements. A later study (Repp 2002b) found exactly the same pattern of tap timing when participants synchronized their taps with an isochronous sequence of clicks that was superimposed on the music (Fig. 4.2b), and even when the participants merely imagined the music in synchrony with the clicks, although the variations were smaller in that case (Fig. 4.2c). When synchronizing with the clicks without imagining music, the average inter-tap intervals were essentially constant (Fig. 4.2a).

The original hypothesis leading to this research (Repp 1999a) was that the patterning of the taps would reflect expectations of expressive timing. However, there was only a weak resemblance between the timing pattern of the taps and the typical expressive timing profile of the music. The timing of the taps seemed to reflect more the metrical structure of the music, whereas expressive timing primarily reflects the melodic–rhythmic grouping structure. Similar conclusions were reached in a study that investigated tapping with two complete Preludes by Chopin (Repp 1999c). However, the structural determinants of tap timing in this situation have not been fully unravelled and are in need of further investigation.

Repp (1999b, 2002b) used the same Chopin Etude excerpt to investigate participants' ability to synchronize with expressively timed music. In the earlier study (Repp 1999b), the participants were pianists who had just played the excerpt on a digital piano. When they were asked to tap along with one of their own recorded performances or with a synthesized performance having a typical expressive timing pattern, they were clearly able to anticipate the expressive timing variations, but not perfectly: large deviations from regularity were usually underestimated, and the resulting asynchrony had to be corrected on the next tap(s). The later study (Repp 2002b) compared synchronization of taps with three kinds of sequences: expressively timed music; a monotone sequence with the same timing pattern; and music with an atypical or structurally inappropriate (phase-shifted) expressive timing pattern. Synchronization with the expressively timed music was relatively most accurate, and interestingly this advantage was already evident on the first trial. Thus, hearing the musical structure helps predict appropriate variation of expressive timing.

Fig. 4.2 Average inter-tap interval (ITI) profiles with double standard errors in three synchronization conditions: (a) tapping with an isochronous (iso) sequence of clicks; (b) tapping with the same sequence of clicks accompanied by isochronous music; (c) tapping with the same sequence of clicks while merely imagining the music in synchrony with the clicks. The initial three ITIs reflect the 'tuning in' to the sequence tempo. (From Repp 2002b.)
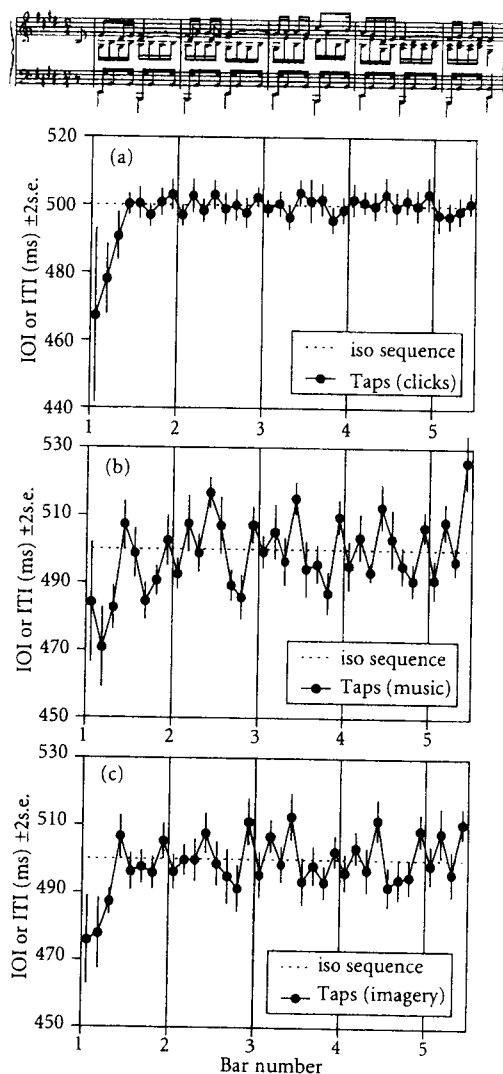
Synchronization with all three sequence types improved with practice (Repp 2002b). Initially, participants' prediction of the timing variation was relatively poor, and this was reflected in a large lag-1 correlation and a small lag-0 correlation between the sequence inter-onset intervals and the inter-tap intervals. In other words, participants mainly reacted to the variation in timing, tracking it rather than predicting it. In the course of 10 trials, however, the lag-1 correlation gradually decreased and the lag-0 correlation increased, which reflects increasing prediction. These changes can be interpreted in terms of the two error correction mechanisms, phase correction and period correction (see section on Error
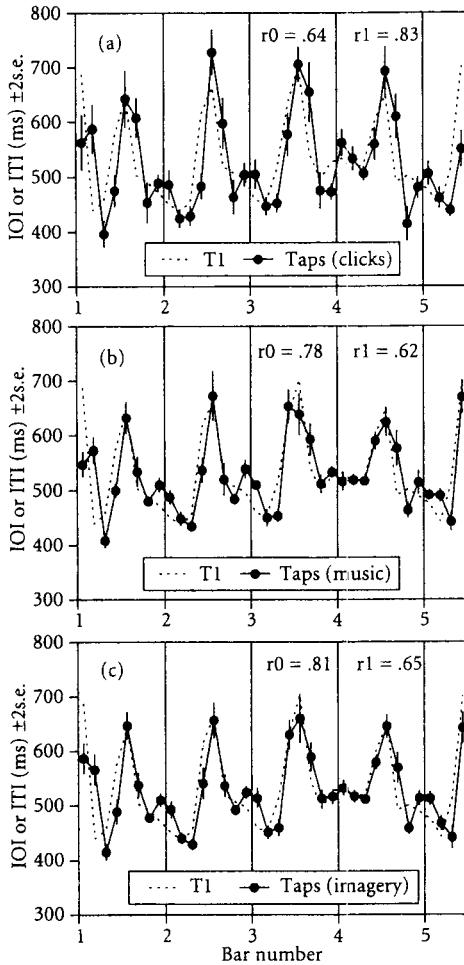
Fig. 4.3 Average inter-tap intervals (ITIs) with double standard errors in three synchronization conditions: (a) tapping with a sequence of clicks whose inter-onset intervals (IOIs) vary according to an 'expressive' timing pattern (T1); (b) tapping with the same sequence of clicks accompanied by music having the same (fairly typical) expressive timing pattern; (c) tapping with the same sequence of clicks while merely imagining the music in synchrony with the clicks. The lag-0 and lag-1 correlations between the IOIs and ITIs are also given (r0 and r1, respectively). Note the increase in r0 and the decrease in r1 in the latter two conditions relative to the first condition. (From the electronic appendix to Repp 2002b.)

correction above). Phase correction is the automatic reactive mechanism that causes tracking, whereas period correction is the predictive mechanism. Expectation and active prediction of a learned timing pattern presumably involve an intentional modulation of the period of the internal timekeeper. As learning proceeds, prediction via period correction improves, so that there are smaller asynchronies for phase correction to react to.

Figure 4.3 illustrates the relative accuracy of synchronizing with an expressive timing pattern that is fairly typical for performances of the excerpt from the Chopin Etude. Inter-tap intervals averaged across a number of trials and participants are shown for three conditions: synchronization with (a) a sequence of clicks with 'expressive' timing but without accompanying music, (b) the clicks accompanied by the synchronous music, and (c) the clicks while the music is merely being

imagined. The target timing pattern is shown as the dotted line. Note that the initial underprediction of large deviations is smaller in the second and third conditions than in the first condition, and this is reflected in an increased lag-0 correlation (prediction) and a decreased lag-1 correlation (tracking).

Marching and dancing to music

There have been very few systematic studies of activities other than finger tapping in synchrony with music. It can be safely assumed, however, that the basic principles revealed by finger-tapping studies also apply to other forms of synchronized movement, especially if they involve periodic contacts with a surface. That is true for the feet in both marching and dancing, whereas the arms and the body move more freely. Direct comparisons between continuous (free) and discontinuous (contact) movements in an SMS task remain to be conducted.

In this context, it should be noted that music has been used in a clinical setting to improve the gait patterns of stroke victims and patients with Parkinson's disease (see Thaut *et al.* (1999) for a summary). These patients readily entrained their steps to the music and derived greater benefits from rehabilitation training than did control groups. Thaut *et al.* hypothesized that there is a direct pathway from the auditory system to spinal motor neurons, which enables rhythmic input to drive motor action.

Synchronization of complex movements with simple sequences

Playing music in synchrony with a metronome

Playing music with a metronome is a task familiar to all music students, especially pianists. Surprisingly, however, it has not been studied in detail. In what seems to be the only study in the literature, Repp (1999c) asked pianists to play two Chopin Preludes in synchrony with a metronome and compared the results to playing without a metronome but in strict time (i.e. without any expressive timing). The main difference was that the correlation between successive inter-beat intervals was negative when playing with a metronome but positive when playing merely in strict time. The Wing–Kristofferson model predicts a negative lag-1 autocorrelation in self-paced rhythm production. The reason why a positive correlation was obtained instead is that there is residual expressive timing variation in performances intended to be in strict time (Penel and Drake 1998; Repp 1999b), and this systematic variation entails positive covariation of successive intervals. The emergence of a negative correlation in the metronome-paced condition was attributed to phase correction in synchronization. In both conditions, the timing of beats was much more regular than in normal expressive performance.

Interestingly, however, the key depressions between beats (i.e. rhythmic subdivisions) showed large deviations from regularity that were hardly affected by either synchronization with a metronome or by the mere intention to play in strict time. Thus, regularity at the beat level does not imply more regular timing at a lower metrical level.

Tapping rhythms in synchrony with a metronome or rhythm template

A recent study (Repp *et al.* 2005) investigated the tapping of 'uneven' rhythms at various tempi. In such rhythms, the inter-beat intervals are not divided evenly. The rhythms included three sets: 2 + 3, 3 + 2; 2 + 2 + 3, 2 + 3 + 2, 3 + 2 + 2; 2 + 3 + 3, 3 + 2 + 3, 3 + 3 + 2. The distinction among the rhythms within each set rested solely on which element was considered as the metrical (down)beat. The rhythms were produced in four conditions: self-paced; synchronized with a metronome, such that the downbeat taps coincided with the tones; synchronized with a precise rhythm template; and synchronized with a rapid isochronous sequence of subdivisions. The last condition served to determine the rate limit of synchronization (see section on Variability above), which was found to be considerably higher than for tapping with every fourth tone of a rapid sequence (Repp 2003), presumably due to the greater cognitive demands of uneven rhythms.

The conditions of main interest here are the other two synchronization tasks. There were four noteworthy findings. First, a characteristic distortion of the 3:2 interval ratios in the direction of 2:1 was equally present in free tapping and in synchronization with a precise rhythm template. In other words, synchronization did not increase the precision of rhythm production. Second, in tapping with a template, the downbeat tap was not synchronized more accurately than the subdivision taps. Rather, the taps generally seemed to be timed so as to minimize the mean asynchrony per rhythm cycle. Third, the asynchronies of the downbeat taps were very different in synchronization with a simple metronome than in synchronization with a rhythm template. In the former condition, they were the only taps that generated asynchronies and thus were the only asynchronies to be minimized, whereas in the latter condition, two or three asynchronies per cycle had to be balanced. Finally, which of the rhythm elements was considered the downbeat had little effect on timing and synchronization. However, the position of a tap in a rhythmic group had a strong effect on its asynchronies with a pacing sequence.

Franêk *et al.* (1988) also found that participants could not synchronize very accurately with cyclically repeated rhythms when they embodied complex interval ratios. Various other studies (e.g. Semjen and Ivry 2001; Semjen

and Vos 2002) have used a metronome to pace bimanual tapping or other periodic bimanual movements having complex interval ratios. However, those studies focused on the bimanual interaction, which is beyond the scope of this chapter.

Synchronization of complex movements with complex sequences

Playing music in an ensemble

One important topic still in need of investigation is synchronization between two individuals, even with a task as simple as tapping simultaneously or in alternation. In such a situation, each participant provides the pacing sequence for his or her partner, and phase correction (as well as perhaps period correction) will occur in both sequences. Preliminary work on such dyadic interactions has been reported by Himberg and Cross (2004) for finger tapping and by Boker and Rotondo (2003) for dancing.

Rasch (1979) measured the mean 'asynchronization' occurring between the players of three professional trios playing classical music. Asynchronization was defined as the 'root mean square of the standard deviation of the onset difference times for all pairs of voices' (p. 123) and was found to range from about 30 to 50 ms. Synchronization was better at fast than at slow tempi. Shaffer (1984) used Rasch's measure to examine the coordination between two pianists in duet playing and found asynchronization of similar magnitude, despite considerable expressive timing variation. Evidently, the pianists were able to predict each other's expressive timing to a considerable extent. In both studies, however, the musicians were able to take advantage of visual as well as auditory cues for coordination.

A recent study (Keller *et al.* in press) examined synchronization accuracy in pianists playing duets with recorded performances of one part of the duet, so that visual cues were not available. The main question was whether pianists would be more accurate synchronizing with performances recorded by themselves than with performances recorded by other pianists. This was indeed found to be the case, although the difference was small. Keller *et al.* attributed it to implicit action knowledge which enables players to predict their own expressive timing patterns better than those of other players.

Friberg and Sundström (2002) measured the relative timing of tone onsets in excerpts from recorded performances by great jazz musicians. They found that the 'swing ratio', a characteristic long–short pattern, was more pronounced in the playing of drummers than in soloists. This implies asynchronies between soloist and drummer. In contrast to the finding by Repp *et al.* (2005) that the mean asynchrony per cycle tends to be minimized when synchronizing a rhythm with a

template, Friberg and Sundström found that soloists lagged behind drummers on the downbeat but were synchronized precisely on the off-beat. This may reflect an expressive strategy of 'playing behind the beat' as well as the structural importance of off-beats in jazz. Other preliminary observations about synchronization in jazz performance have been reported by Prögler (1995) and Schögler (1999–2000).

Ensemble playing requires not only in-phase synchronization with other players but also precise alternation (anti-phase coordination) and other, more complex, forms of rhythmic coordination, as in African drumming or Balinese gamelan. Keller (1999, Keller and Burnham 2005) required percussionists to produce a memorized rhythm concurrently with a different, computer-controlled rhythm in the course of a study of 'prioritized integrative attending' (i.e. attending to one's own part as well as to the integrated rhythm of several parts (Keller 2001)). Synchronization accuracy was assessed only in a qualitative way. More studies of this degree of sophistication and realism are needed to close the gap between laboratory SMS research and actual music performance.

Following a conductor's gestures

Another interesting area awaiting investigation is synchronization of music performance with a conductor's movements, which are often far more complex than a simple beat pattern. Some preliminary work has been conducted by Luck (2002, 2004). He recorded the arm movements of several conductors when they gave a downbeat, reproduced the movement trajectory on a computer screen, and asked participants to make a single tap when they perceived the downbeat as occurring. By manipulating the shape and velocity pattern of the trajectory, he determined that velocity and acceleration were important in conveying a downbeat, but the relative importance of different variables varied from conductor to conductor.

Conclusions

A large number of SMS studies using simple movements and simple auditory sequences has laid the theoretical and empirical groundwork for a more detailed study of the synchronization skills required in music performance, dance, and some athletic disciplines. The SMS research in these latter areas is still very limited. The present chapter (which makes no claim to be comprehensive) has mentioned some relevant studies and has pointed out topics awaiting more careful study. Clearly, here is a potentially rich area for research, the results of which will be of both theoretical interest and of practical relevance.

Acknowledgements

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