Sensorimotor synchronization:
A review of the tapping literature

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Sensorimotor synchronization (SMS), the rhythmic coordination of perception and action, occurs in many contexts, but most conspicuously in music performance and dance. In the laboratory, it is most often studied in the form of finger tapping to a sequence of auditory stimuli. This review summarizes theories and empirical findings obtained with the tapping task. Its eight sections deal with the role of intention, rate limits, the negative mean asynchrony, variability, models of error correction, perturbation studies, neural correlates of SMS, and SMS in musical contexts. The central theoretical issue is considered to be how best to characterize the perceptual information and the internal processes that enable people to achieve and maintain SMS. Recent research suggests that SMS is controlled jointly by two error correction processes (phase correction and period correction) that differ in their degrees of cognitive control and may be associated with different brain circuits. They exemplify the general distinction between subconscious mechanisms of action regulation and conscious processes involved in perceptual judgment and action planning.

Sensorimotor synchronization (SMS) is a form of referential behavior (Pressing, 1999) in which an action is temporally coordinated with a predictable external event, the referent. Usually, the term *SMS* refers to a situation in which both the action and the referent are periodic, so that the predictability of the referent arises from its regular recurrence. SMS thus can be said to involve the temporal coordination of a motor rhythm with an external rhythm. Such coordination is of fundamental importance in musical activities. Musicians playing in an ensemble must synchronize their actions with the audible and visible actions produced by other members of the ensemble. Orchestral musicians must, in addition, follow the gestures of a conductor. During practice, classical musicians often use a metronome to pace their actions. Jazz and popular musicians coordinate their actions with beats produced by the rhythm section of a band or with a click track during recording. Soldiers march to music, and dancers dance to it. When people listen to music, they generate temporal expectations (a form of covert, internal synchronization), and they may move in synchrony with the musical beat.

It is intriguing that although rhythmic synchronization of sound or light emissions is observed within a limited frequency range in some amphibians and insects (see, e.g., Buck & Buck, 1968; Sismondo, 1990), it is rarely, if ever, observed in primates and other mammals (Fraisse, 1974), with the possible exception of bonobos (Merker, 1999/2000, 2000). In contrast to humans, animals do not spontaneously move in synchrony with rhythmic auditory or visual stimuli, and there seem to have been no successful attempts to train them to do so (as has been noted by Patel, Iversen, Chen, & Repp, 2005). In particular, the ability to engage in SMS over a wide range of tempi may be specifically human and could have played an important role in the evolution of music and even of language (Merker, 1999/2000, 2000).

Laboratory studies of SMS frequently focus on the simple task of finger tapping to an auditory sequence consisting of tones or clicks. However, there are many variants of SMS tasks, arising from different forms of movement (e.g., tapping on a hard surface vs. finger flexion or limb movement without contact), different modalities of stimulation (e.g., auditory or visual), and different forms of coordination (e.g., in-phase or antiphase; see Figure 1).[1] Research on SMS started long ago (Dunlap, 1910; I. Miyake, 1902; Stevens, 1886; Woodrow, 1932), but the most important pioneers were Paul Fraisse in the 1950s–1970s and John Michon in his 1967 dissertation. There has been a notable increase in research activity in recent years, which makes the present review seem timely. Its aim is to give an overview of theories and findings from the perspective of someone with a particular interest in music performance and its component skills. Therefore, the finger-tapping task takes center stage because it is arguably more relevant to musical sound production, particularly on keyboard and percussion instruments, than are studies of contact-free limb movement.
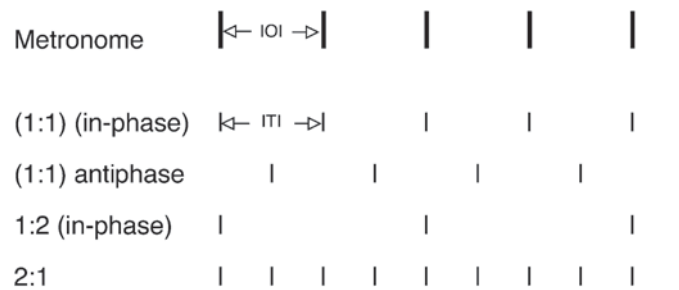
Figure 1. Common coordination modes in sensorimotor synchronization experiments. Small vertical bars stand for taps. Interonset interval (IOI) and intertap interval (ITI) are indicated. Terms in parentheses are generally implied, when not mentioned explicitly.

Two main theoretical approaches to SMS can be distinguished: information-processing theory and dynamic systems theory. The former generally deals with responses represented as a discrete time series, whereas the latter is concerned primarily with continuous movement, represented as a trajectory in phase space. Furthermore, information-processing approaches aim to describe hypothetical internal processes underlying behavior, whereas dynamic systems approaches are concerned with the mathematical description of observable synergies. Control theory (Jagacinski & Flach, 2003), which is used more in engineering applications than in psychological research, occupies a middle ground. For an illuminating discussion of how these theoretical approaches to SMS are related, see Pressing (1998b, 1999). It is likely that each approach is suited to explain some aspects of SMS better than others. Because tapping on a surface generates discrete events, most researchers using that paradigm have taken an information-processing perspective (and vice versa), whereas dynamic systems theorists have generally preferred continuous movement tasks. Although dynamic systems theory is sufficiently general to encompass both continuous and discrete forms of periodic movement, the latter may not simply be special cases of the former: Movements that are organized as a series of discrete contacts seem to require more explicit temporal control than do continuous movements (Delignières, Lemoine, & Torre, 2004; Zelaznik, Spencer, & Ivry, 2002), and thus, they also may involve different brain circuits, particularly the cerebellum (Spencer, Ivry, & Zelaznik, 2005; Spencer, Zelaznik, Diedrichsen, & Ivry, 2003). It has also been observed that paced finger movements (without surface contact) are more asymmetric than unpaced ones and, thus, more difficult to accommodate by an oscillator model (Balasubramaniam, Wing, & Daffertshofer, 2004).

Most of the research to be reviewed here was conducted by scientists taking an information-processing approach, including the present author. Therefore, the dynamic systems perspective will be mentioned only occasionally. This should not be taken to imply that the author disdains that approach or the research that it has generated; quite the contrary. Rather, the imbalance is dictated by practical considerations. The author does not see any fundamental incompatibility between the two approaches, and although at present they are associated largely with different models, different terminology, and different experimental paradigms, he believes that they will merge eventually.

1. THE ROLE OF INTENTION

It may seem strange to begin a review with the role of intention, but it is often forgotten that human behavior observed in the laboratory crucially depends on participants' willingness to follow instructions. SMS is normally an intentional activity and, by definition, an overt one, because it involves movement. First, to engage in SMS, a person must intend to move. Although movement in synchrony with a rhythmic beat may occur unintentionally, it can easily be suppressed when attention is paid to it, as is shown by audiences sitting still during a concert performance. Second, the person must intend to coordinate the movement with an external referent. It is perfectly possible to tap at one tempo while listening to an auditory sequence of beats at a different tempo (Repp, 2006a) or to march out of step with music.

Nevertheless, SMS is difficult to avoid in certain situations that involve both movement and periodic stimulation. Klemmer (1957, 1967) found that in a task requiring rapid responses to auditory or visual stimuli occurring in an isochronous sequence, the responses tended to precede, rather than follow, the stimuli when the sequence interonset intervals (IOIs) were relatively short. That is, the responses effectively became entrained by the stimuli and turned into anticipations, characteristic of SMS (see also Engström, Kelso, & Holroyd, 1996; Fraisse, 1966). The tendency of taps to precede stimuli in SMS will be discussed in more detail in Section 3.

Intermittent entrainment of periodic movement to a stimulus sequence (also referred to as *relative coordination*) may occur unintentionally, especially when the respective period durations are similar. Schmidt and O'Brien (1997) asked participants to swing a pendulum at a comfortable tempo while observing another participant doing the same. Although the individual tempi did not converge, analysis of the distribution of relative phases revealed that whenever the pendulum movements converged onto

an in-phase relationship, they stayed somewhat longer in that relationship than would be expected by chance, before drifting apart again (see also Richardson, Marsh, & Schmidt, 2005). Similar findings were obtained in a recent study of self-paced finger tapping in the presence of a to-be-ignored auditory tone sequence (Repp, 2006a): Although participants were able to maintain the tapping tempo established during synchronization with a preceding pacing sequence, they exhibited relative coordination with the distractor sequence, albeit only when the tapping and the distractor periods were similar.

If a person intends to coordinate movement with a stimulus sequence in a particular way, the intended mode of coordination may become unstable and may change to a different mode as the tempo of the pacing sequence is increased. This phenomenon, known as a *phase transition*, has been of central interest to dynamic systems theorists, because it helps identify the kind of dynamic system under study. The transition is usually observed from antiphase to in-phase coordination. It has been investigated most often in the context of bimanual coordination (a large topic beyond the scope of this review), where it has led to an influential model of coordination dynamics (Haken, Kelso, & Bunz, 1985). However, phase transitions have also been demonstrated in SMS tasks (Kelso, DelColle, & Schöner, 1990; Repp, 2005c; Volman & Geuze, 2000; Wimmers, Beek, & van Wieringen, 1992). A phase transition may result in lack of coordination (phase wandering) when participants are specifically instructed to avoid in-phase synchronization (Smethurst & Carson, 2003).

Phase relationships other than in-phase or antiphase ones are even more difficult to maintain and tend to revert to the more stable coordination modes. This was also first demonstrated in bimanual coordination (Yamanishi, Kawato, & Suzuki, 1980), although the instability may not originate in the movements themselves but may arise at a perceptual or cognitive level (Mechsner, Kerzel, Knoblich, & Prinz, 2001; Semjen & Ivry, 2001). In SMS, when an auditory sequence is phase shifted by a small amount during in-phase tapping and participants are instructed to maintain the new phase relationship, many of them will drift back into synchrony against their will (Repp, 2002f). This can happen even when the phase shifts by as much as half a cycle, so that participants find themselves unexpectedly in antiphase mode (Semjen, 2000). Furthermore, when a target sequence for SMS is accompanied by a distractor sequence at a fixed or continuously changing phase relationship, participants sometimes synchronize with the distractor sequence without noticing it (Repp, 2003a).

Thus, there are quite a few situations in which in-phase SMS can occur unintentionally. Conversely, unintentional deviations from SMS may be caused by perturbations or distractor stimuli. These effects will be reviewed in Section 6.

2. RATE LIMITS

SMS with an isochronous auditory sequence (i.e., a metronome) is possible only within a certain range of frequencies (as dynamic systems theorists would say) or sequence IOIs (the metric commonly used in information-processing approaches). Fraisse (1982) gave the IOI range as 200–1,800 msec. Actually, the lower IOI limit (or upper rate limit) for 1:1 in-phase synchronization tends to be set by the maximum frequency at which the effector can move. For finger tapping, that is typically 5–7/sec, which corresponds to intertap intervals (ITIs) of 150–200 msec (Keele & Hawkins, 1982; Keele, Pokorny, Corcos, & Ivry, 1985; Peters, 1980, 1985; Todor & Kyprie, 1980; Truman & Hammond, 1990). Up to that limit, the task presents no difficulties, at least for participants with musical training (Repp, 2005d). When the biomechanical limit is avoided by changing the task to 1:*n* synchronization, so that a tap is made with only one out of every two, three, or four tones (see Figure 1 for an example of 1:2 tapping), it becomes clear that there is an even lower IOI limit of a perceptual or sensorimotor nature (Bartlett & Bartlett, 1959). For musically trained participants, that limit (the *synchronization threshold*) lies typically at IOIs of 100–120 msec (Repp, 2003b). Below that limit, taps and tones usually drift apart, and participants seem unable to perceive whether or not they are in synchrony. Another way to avoid the biomechanical limit is to tap with both hands in alternation. In that fashion, the late Jeff Pressing, a highly trained musician, was able to synchronize in a 1:1 mode up to a tempo with an IOI of 100 msec (Pressing & Jolley-Rogers, 1997).

There is also an upper IOI limit (or lower rate limit) for SMS with a metronome sequence, although it is less sharply defined. A crucial aspect of SMS is the prediction of future events: Although each tap may be regarded as the response to a preceding tone, it is a *timed* response that is delayed so as to coincide approximately with the next tone. This distinguishes SMS from a simple reaction time task, where the response is made as quickly as possible. When metronome IOIs exceed about 1.8 sec, prediction becomes increasingly difficult, and responses begin to lag behind their respective target events (Engström et al., 1996; Mates, Radil, Müller, & Pöppel, 1994; Y. Miyake, Onishi, & Pöppel, 2004). In other words, when responses can no longer be timed accurately enough to coincide with the next tone, some responses turn into simple reactions to that tone, and this results in a bimodal distribution of asynchronies. This tendency is further enhanced when the participants' attention is diverted by a secondary task (Y. Miyake et al., 2004). However, it does not occur in antiphase coordination, because there is no event to react to at the IOI midpoint (Engström et al., 1996).

It is well established that antiphase tapping is more difficult than in-phase tapping, and accordingly, its lower IOI limit is a good deal higher than that for in-phase tapping. Some musically untrained participants may already begin to experience difficulties when the metronome IOIs are less than 1 sec (Fraisse & Ehrlich, 1955). The breakdown of antiphase synchronization is often (but not always) manifested as an involuntary switch to in-phase synchronization. Researchers who investigate antiphase coordination from a dynamic systems perspective (e.g., Kelso

et al., 1990) are usually not concerned especially with estimating the lower IOI limit: They instruct participants not to resist the phase transition, so the self-organizing task dynamics can be observed without interference. When musically trained participants try hard to maintain antiphase tapping with auditory sequences at increasingly faster tempi, they typically encounter difficulties when the IOI is less than 350 msec, although some can still manage 300 msec (Repp, 2005c, 2005d). Interestingly, whereas in-phase tapping is as easy with alternating hands as with a single hand, antiphase tapping appears to be more difficult with alternating hands, presumably because of the additional bimanual antiphase relation that this task introduces (Keller & Repp, 2004). Antiphase tapping may be aided by regular metrical accents that enable periodic phase resetting (Keller & Repp, 2005).

Although these rate limits may be relevant to certain extreme situations in music ensemble performance, fast music usually contains periodic regularities at slower time scales that can aid SMS, whereas the beats of slow music are usually subdivided. The rate limits are of theoretical interest mainly because they reveal general constraints on temporal processing. The lower and upper IOI limits of SMS are in the vicinity of changes in the relation between variability and interval duration, which suggests a common cause. Between approximately 250 and 2,000 msec, variability of both interval perception and interval production increases steadily with interval duration, approximately following Weber's law (Madison, 2001). Beyond 2,000 msec, however, variability increases disproportionately (Getty, 1975), whereas below 250 msec, it stops decreasing, so that it increases steeply as a proportion of the IOI or ITI (Friberg & Sundberg, 1995; Peters, 1989). High absolute or relative variability obviously is an impediment to SMS.

The lower and upper IOI limits for SMS may represent perceptual temporal integration windows of different duration. The lower IOI limit is somewhat shorter than the 160- to 170-msec duration of an auditory integration window estimated in studies of the mismatch negativity (a kind of evoked brain potential) by Yabe, Tervaniemi, Reinikainen, and Näätänen (1997; Yabe et al., 1998). When sounds fall within this integration window, they seem to be perceived as a tightly bound group, rather than as separate events. Musically trained individuals may have particularly narrow integration windows allowing optimal temporal resolution of events. Other evidence suggests that the shortest duration of tones that can function as individual elements in a musical rhythm is around 100 msec (Friberg & Sundström, 2002; London, 2002, 2004); even shorter tones tend to be perceived as grace notes or ornaments. The upper IOI limit of about 1.8 sec has been related to the duration of the *subjective present* and the temporal capacity of working memory (Pöppel, 1997; Szelag, von Steinbüchel, Reiser, de Langen, & Pöppel, 1996; Wittmann & Pöppel, 1999/2000). More generally, the IOI limits for SMS coincide with those within which a sequence of events can be perceived to have rhythmic and metrical structure (Bolton, 1894; Fraisse, 1982; London, 2004). A variety of other temporal phenomena, too numerous to be discussed here, are potentially related to each of these limits (see also Section 7).

The lower IOI limit for antiphase tapping may be related to the IOI limit for in-phase tapping. Antiphase tapping requires bisection of the IOI, because the IOI midpoint is the synchronization target. Thus, the functional interval duration is half the IOI. Repp (2005d) found the mean IOI limit for antiphase tapping (350 msec) to be about twice as large as the one for 1:2 in-phase tapping (182 msec). The latter value was higher than the one obtained for 1:4 in-phase tapping by Repp (2003b) because a more stringent accuracy criterion was employed, not because of a task-related difference. A recent study (Repp, 2005a) compared 1:2 and 1:4 in-phase tapping and showed no significant difference in IOI limits.

Another rate limit related to subdivision has been described by Repp (2003b): The variability of asynchronies in 1:1 in-phase tapping are reduced when the IOIs between target tones are subdivided explicitly by additional tones, turning the task into 1:*n* tapping. This *subdivision benefit* disappears, however, when the subdivision IOI duration is shorter than 200–250 msec (see also Semjen, Schulze, & Vorberg, 1992) and, as the tempo is increased further, turns into a cost (an increase in variability) that eventually leads to the synchronization threshold.

In recent studies, the lower IOI limit has been explored for somewhat more complex SMS tasks, often with the help of an adaptive staircase method. Repp (2005a) found that 1:5 and 1:7 tapping (i.e., tapping with every fifth or seventh tone in a rapid isochronous sequence) have substantially higher synchronization thresholds than do 1:2, 1:3, 1:4, and 1:8 tapping, which do not differ significantly; 1:6 and 1:9 tapping fall in between. Apparently, repeated counting of a prime number, which can be subdivided only into unequal integer parts, makes cognitive demands that interfere with the temporal resolution of sequence events and/or with phase error correction. The thresholds for 1:6 and 1:9 tapping tasks may be elevated because they require triple subdivision. These results illustrate the spontaneous emergence of metrical structure in SMS tasks that require keeping count of rapid events, a phenomenon closely related to the *subjective rhythmicization* of uniform sequences (Bolton, 1894; Fraisse, 1982). Repp, London, and Keller (2005) found a correspondingly high synchronization threshold for tapping *uneven* rhythms such as 2+3 or 2+3+3 in synchrony with a rapid metronome. For example, for the 2+3 rhythm, the participants had to tap with the first and third tones in every group of five metronome tones. This explicit subdivision of a longer interval into unequal parts also seems to have required mental resources that otherwise would have facilitated synchronization.

Repp (2005c, 2005d) investigated the lower IOI limits for tapping with nonisochronous sequences. The sequences represented simple rhythms consisting of cyclically repeated groups of two or three tones, with the between-groups IOI being twice as long as the within-group IOI. Participants were asked to tap isochronously

with a particular tone in each cycle or in the middle of the between-group IOI. The results showed the lowest IOI limits for tapping with the final tone in groups of two tones and with the initial or final tones in groups of three tones. These are the tones that carry a *rhythmic grouping accent* (Povel & Essens, 1985; Povel & Okkerman, 1981) and, therefore, are also likely carriers of the metrical beat. Tapping with the middle tone in a group of three was as difficult as tapping with the empty midpoint of the between-group IOI. Repp (2005c, 2005d) also showed that it is easier to tap with physically (intensity/pitch) accented tones than with unaccented tones, independently of their group position, but he could not demonstrate a consistent effect of subjectively manipulated metrical accent. A subsequent study in which isochronous melodies were used, however, was more successful in showing that synchronization thresholds are lower when participants tap on a self-imposed beat (i.e., on metrically accented tones) than when they tap off that beat (Repp, 2005b).

It is noteworthy that the lower IOI limit for in-phase tapping with a visual stimulus sequence is much higher than that with an auditory sequence. Repp (2003b) found that synchronization with a flashing light became impossible when the IOIs were shorter than about 460 msec (see also Bartlett & Bartlett, 1959; Dunlap, 1910). The synchronization threshold thus is about four times as high for (stationary) visual than for auditory stimuli! The upper IOI limit, however, seems to be similar for SMS with visual and auditory sequences (Engström et al., 1996; Mates et al., 1994). The extent to which SMS may be facilitated when the visual display includes movement or a change in object shape or color remains to be investigated. However, it seems unlikely that the synchronization threshold will ever be as low as that for auditory stimuli. This striking modality difference has not yet received a satisfactory explanation. Although it is consistent with better temporal resolution in the auditory modality and with higher variability of tapping with visual than with auditory sequences (Kolers & Brewster, 1985; Repp & Penel, 2002, 2004), the synchronization threshold difference is much larger than one would expect on these grounds. Fraisse (1948) thought that there was a closer neural connection between auditory perception and movement than between visual perception and movement. Thaut, Kenyon, Schauer, and McIntosh (1999) suggested more recently that a fairly direct connection exists between the auditory cortex and spinal motor neurons, which enables auditory rhythms to entrain motor behavior. This is an important possibility that needs to be investigated in more detail.

3. THE NEGATIVE MEAN ASYNCHRONY

Some of the earliest investigators of SMS (I. Miyake, 1902; Woodrow, 1932) noted that taps tend to precede sequence tones by a few tens of milliseconds, rather than being distributed symmetrically around the tone onsets. This negative mean asynchrony (NMA),[2] or anticipation tendency, has been found in most SMS studies in the literature and has generated a considerable amount of research (see Aschersleben, 2002, for a recent review). Nevertheless, the causes of the NMA are still not fully understood.

The NMA is small or absent in musical contexts: Musically trained participants tend to show a smaller NMA than do untrained participants (Aschersleben, 2002) and, sometimes, none at all (see, e.g., Repp, 2004b). Moreover, both explicit auditory feedback (Aschersleben & Prinz, 1995) and rhythmic complexity or subdivision (Wohlschläger & Koch, 2000) reduce or eliminate the NMA. The NMA is thus a phenomenon peculiar to nonmusicians tapping in synchrony with a simple metronome.

People are generally not aware of their NMA. Aschersleben (2003) trained participants to achieve zero mean asynchrony by giving them visual feedback about the magnitude and direction of their asynchronies. However, the participants reported that they had to delay their taps in order to achieve their goal. In other words, the points of objective synchrony and subjective synchrony generally do not coincide, at least for nonmusicians. Two other empirical findings place important constraints on explanations for the NMA. One is that the NMA decreases as the sequence IOIs decrease (Mates et al., 1994; Peters, 1989; Repp, 2003b). The other finding is that there are large individual differences: Some individuals tap ahead of the tones by as much as 100 msec, whereas others show hardly any NMA at all (Aschersleben, 2002; Aschersleben & Prinz, 1995; Repp & Penel, 2002).

A number of explanations of the NMA have been suggested, none of which is comprehensive, although each has some merit. Paillard (1948) and Fraisse (1980) thought that the NMA comes about because of different nerve transmission times from the finger to the brain and from the ear to the brain. Initial support for this idea came from findings that the NMA is larger for foot tapping than for manual tapping (Aschersleben & Prinz, 1995; Aschersleben, Stenneken, Cole, & Prinz, 2002; Billon, Bard, Fleury, Blouin, & Teasdale, 1996; Fraisse, 1980). However, this difference could well be due to the different kinematics of foot versus finger movement, and the nerve transmission hypothesis cannot easily explain large individual differences or the dependence of the NMA on sequence tempo. Aschersleben (2002; Aschersleben, Gehrke, & Prinz, 2004) proposed, instead, a sensory accumulator model, according to which consciously perceived synchrony is achieved by accumulating evidence at different rates from different sensory channels. Each rate of accumulation, up to some criterion of sufficiency, is determined by the magnitude of the input and by the sensory modality itself.

One cause of the NMA does seem to be a slower central registration of tactile and proprioceptive information, as compared with auditory information. The NMA decreases when the auditory feedback from taps is enhanced by making a tone contingent on each tap (Aschersleben & Prinz, 1995, 1997), and it increases when the tactile feedback from the finger is reduced through anesthesia (Aschersleben, Gehrke, & Prinz, 2001). The NMA is also sensitive to manipulations of auditory feedback delay (Aschersleben & Prinz, 1997; Fraisse, Oléron, & Paillard,

1958; Mates & Aschersleben, 2002). Perceived synchrony thus seems to depend on all available forms of sensory evidence. Individual differences, including those of musical training, could be attributed to different weightings of different sensory modalities. It certainly makes sense to assume that musicians pay more attention to auditory feedback than do nonmusicians. The decrease of the NMA with increasing tempo could be explained by assuming that more tactile and proprioceptive feedback is received from fast than from slow taps (Aschersleben, 2002). Whether that is really the case requires further study.

A particularly interesting finding is that completely de-afferented individuals (suffering from a rare disorder that eliminates all tactile or kinesthetic sensations from the body) can tap in phase with a metronome even when they are prevented from seeing or hearing their taps (Aschersleben et al., 2002; Billon, Semjen, Cole, & Gauthier, 1996). Obviously, the sensory accumulator model cannot account for that feat. Aschersleben et al. (2002) proposed, instead, that internally simulated action consequences are being synchronized with the metronome. Deafferented individuals also show a large NMA, which suggests that they first issue a motor command to the finger and then imagine its potential sensory consequences (most likely, visual or auditory) in synchrony with the metronome.

In the *virtual amplitude* model of tapping (Vaughan, Mattson, & Rosenbaum, 1998; Vaughan, Rosenbaum, Diedrich, & Moore, 1996), the finger movement is considered to be an oscillation that is interrupted by contact with a surface. The virtual target of the tap is assumed to be the velocity minimum that the oscillation would reach if it were unimpeded. If this virtual target were the basis of perceived synchronization, an NMA with respect to the point of contact would result. This model can also account for the decrease in the NMA with increasing tempo, because the amplitude of an oscillation tends to decrease as the frequency increases, which in turn reduces the delay of the virtual target, relative to the contact point (see Figure 6 in Vaughan et al., 1996). Individual differences could be explained by differences in tapping kinematics. Effects of auditory feedback cannot be explained by this model, however.

From a dynamic systems perspective, tapping can be regarded as an oscillatory motor activity that is weakly coupled (via perception) to an external driving oscillator, the pacing sequence (Pikovsky, Rosenblum, & Kurths, 2001). It is well known that a mismatch between the natural frequencies of coupled oscillators (known as *detuning*), if it is not too large, causes a phase lag, so that the intrinsically faster oscillator leads the intrinsically slower one (see, e.g., Yu, Russell, & Sternad, 2003). On this basis, an NMA is predicted if the natural frequency of the tapping finger is higher than that of the metronome. Moreover, a decrease in the NMA is predicted as the metronome frequency approaches the natural frequency of the finger. A natural period of about 250 msec (as has been suggested by Roberts, Eykholt, & Thaut, 2000) would be consistent with this hypothesis. However, participants typically make only about two taps per second when asked to tap at their most comfortable rate (see, e.g., Drake, Jones, & Baruch, 2000). Collyer, Boatright-Horowitz, and Hooper (1997; Collyer, Broadbent, & Church, 1992, 1994) have found an *oscillator signature* in the variability of self-paced finger tapping at a wide range of tempi, suggesting two natural periods—one at about 250 msec and the other at 500–600 msec. Perhaps the shorter period reflects the natural frequency of the finger, whereas the longer period (which resembles that of the preferred rate of tapping, as well as that of walking) is of cognitive origin. However, the natural frequency of the finger does not seem to have been measured directly and, in fact, may not be easy to determine, because the tapping movement is not strictly oscillatory.

Another proposal has been that the NMA represents an asymmetric cost function (Vos & Helsper, 1992) or error tolerance zone (Müller, Aschersleben, Koch, Freund, & Prinz, 1999). One possible reason why positive asynchronies are associated with a higher cost than are negative ones is that, in the absence of salient auditory feedback from the taps themselves, participants may be inclined to perceive the metronome sounds as consequences of their taps. Tolerance zones could scale with tempo and plausibly exhibit large individual differences.

Yet another account of the NMA rests on a statistical argument based on the assumption that participants try to minimize the variance of their asynchronies (Vorberg & Wing, 1996): Because variability decreases with ITI duration, it can be shown that the variance of asynchronies is minimized when the period of the internal timekeeper or oscillator that is assumed to drive the taps is somewhat shorter than the metronome IOI. This is a form of detuning (in this case, between an internal controller and an external sequence) and results in a phase lead of taps over tones—the NMA. This explanation cannot account, however, for effects of feedback manipulation and large individual differences. Also, there seems to be no strong relation between the NMA and variability.

Finally, a perceptual hypothesis proposed by Wohlschläger and Koch (2000) deserves attention. Wohlschläger and Koch showed that the NMA is reduced or eliminated when participants subdivide the ITI by making additional contact-free movements between regular synchronized taps or when additional tones are interspersed between the metronome beats (see also Repp, 2002a, 2003b; Thaut, Rathbun, & Miller, 1997). Other explanations of the NMA cannot readily account for the latter finding. It appears that any kind of subdivision of the IOI or ITI reduces the NMA, which is why the NMA is generally not evident in tapping to music. On the basis of their findings, Wohlschläger and Koch proposed that the NMA is a consequence of perceptual underestimation of the duration of empty IOIs (see Craig, 1973; Goldfarb & Goldstone, 1963). Such underestimation would lead to a shortened period of the internal timekeeper or oscillator that controls the tapping tempo and, thus, to an NMA. This hypothesis can explain the decrease in the NMA with IOI duration, because underestimation is likely to be proportional to interval duration, and it can accommodate

individual differences as well. Caspi (2002) conducted an experiment in which he asked participants to continue tapping after synchronizing with a series of beats whose IOIs either were empty or contained randomly inserted tones. The continuation tapping was a good deal slower in the second condition than in the first. However, the ITIs of the continuation tapping suggested overestimation of the subdivided IOIs, not underestimation of the empty IOIs. Recent research (Repp, unpublished data) has shown that musically trained participants, who do not show an NMA to begin with, exhibit a robust effect of metrical subdivision on the tempo of continuation tapping, whereas their asynchronies are unaffected. These findings raise problems for the perceptual underestimation explanation of the NMA.

Another perceptual factor that has been shown to affect the magnitude of the NMA is the duration and rise time of the auditory pacing stimuli (Vos, Mates, & van Kruysbergen, 1995). This is in accord with research on *perceptual centers* of stimuli (Morton, Marcus, & Frankish, 1976) but does not explain the NMA phenomenon. McAnally (2002) showed that people can reliably synchronize taps with a continuous frequency-modulated tone and show an NMA, relative to the point of maximal frequency change. The NMA decreased, however, as the modulation depth was decreased.

Some studies have shown a smaller NMA with visual than with auditory pacing sequences (Fraisse, 1948; Kolers & Brewster, 1985; Repp & Penel, 2002); others have shown the opposite (Repp, 2003b; Repp & Penel, 2004). The difference seems to be tempo dependent: Repp (2003b) found that the NMA decreases much faster with visual than with auditory stimuli as the IOI duration is decreased. No current theory accounts for this interaction. The modality difference may also depend on musical training, since musically trained individuals tend to show negligible NMAs with auditory stimuli.

In summary, there are a number of competing, but not mutually exclusive, explanations for the NMA, and it is possible that several of these explanations are needed to account for the full range of findings.

4. VARIABILITY

Synchronization skill appears to be distinct from other rhythmic abilities (Hiriartborde & Fraisse, 1968; Thackray, 1969). The variability of asynchronies and ITIs in an SMS task is one important indicator of a participant's synchronization skill. A musically trained and practiced individual can achieve a standard deviation of asynchronies as small as 2% of the IOI or ITI duration in 1:1 in-phase tapping (see, e.g., Pressing & Jolley-Rogers, 1997; Repp & Penel, 2002), whereas it will typically be at least twice as large for novice participants. Standard deviations of ITIs can be as low as 0.5% in percussionists (Gérard & Rosenfeld, 1995). Variability of SMS decreases during childhood and adolescence and then remains constant during adulthood into old age (Drewing, Li, & Aschersleben, in press). The earliest age at which SMS can be

reliably achieved does not seem to have been determined precisely; Fraisse (1966) gave the age as 3–4 years. In any case, SMS ability seems to develop quite gradually.

The variability of both asynchronies and ITIs decreases as the mean ITI (and IOI) decreases (see, e.g., Michon, 1967; Semjen, Schulze, & Vorberg, 2000).[3] The dependence of ITI variability on ITI duration is a well-known finding for self-paced tapping, which is usually examined in the synchronization–continuation tapping paradigm introduced by Stevens (1886). Wing and Kristofferson (1973a, 1973b; Wing, 1980) proposed a seminal model that partitions the ITI variance into two components: one attributed to a central timekeeper and the other to more peripheral motor implementation. According to this model, only the timekeeper variance depends on ITI duration. Timekeeper variance is also likely to be the main source of individual differences in variability. Motor variance is small relative to timekeeper variance, except at very short ITI durations, and tends to be similar across individuals (Wing, 1980). These relationships presumably apply equally in SMS (Semjen et al., 2000; Vorberg & Schulze, 2002; Vorberg & Wing, 1996), to the extent that the model is accurate. The principal difference between SMS and self-paced tapping is that feedback-based error correction or entrainment occurs in SMS (see Section 5), whereas self-paced tapping is generally assumed to be an open-loop process (but see Wing, 1977). Error correction obviously prevents large asynchronies, as well as substantial tempo drift; nevertheless, it tends to increase the ITI variance slightly, especially at slow tempi (Madison, 2001; Semjen et al., 2000).

Variability depends not only on ITI duration, but also on sequence IOI duration when the two are varied independently. This was mentioned already in Section 2 in connection with the *subdivision benefit* (Repp, 2003b). For a similar reason, the variability of antiphase tapping tends to be lower than that of in-phase tapping at slow metronome rates (IOI > 500 msec), presumably because antiphase tapping entails IOI subdivision (Semjen et al., 1992). At faster rates, this subdivision benefit disappears, and the variability of antiphase tapping remains constant or increases until coordination breaks down (Repp, 2005d). However, when participants are not prepared to tap in antiphase (Semjen, 2000) or when they make a finger movement without contacting a hard surface (see, e.g., Kelso et al., 1990), antiphase coordination tends to be less stable than in-phase coordination, even at relatively slow tempi. This may be so because these conditions do not promote a strategy of mental subdivision of the metronome IOIs.

In models of timing control, it is usually assumed that the sources of variability are random and that sequential dependencies in ITIs and asynchronies result from the hierarchical arrangement of central and peripheral sources of variability (Vorberg & Wing, 1996; Wing & Kristofferson, 1973a, 1973b), as well as from additional error correction processes in SMS (see Section 5). These models predict a negative correlation of successive ITIs, but a positive correlation of successive asynchronies in SMS (Semjen et al., 2000; Vorberg & Schulze, 2002). However, there is in-

creasing evidence that, in addition to such local dependencies, long-range correlations exist in both self-paced tapping and SMS. Spectral analyses of the ITIs of long series of self-paced taps indicate the presence of low-frequency energy of increasing amplitude, variously referred to as *ITI drift*, *fluctuations*, *1/f noise*, *fractal structure*, or *deterministic chaos* (Delignières et al., 2004; Gilden, 2001; Gilden, Thornton, & Mallon, 1995; Madison, 1999, 2001, 2004; Roberts et al., 2000; M. Yamada, 1996; M. Yamada & Yonera, 2001; N. Yamada, 1995). One way of dealing with drift is to incorporate it into the Wing–Kristofferson model as a third variance component and, thereby, to separate it from estimates of timekeeper and motor variance (Collier & Ogden, 2004). It is possible, however, that drift is an inherent property of the internal timekeeper and that different approaches based on dynamic systems theory are required to come to grips with internal timing processes.

During SMS, ITI drift is much reduced because of error correction or entrainment to the pacing sequence, but the asynchronies nevertheless have been found to exhibit long-range dependencies (Chen, Ding, & Kelso, 1997, 2001; Chen, Repp, & Patel, 2002; Roberts et al., 2000). Interestingly, the strength of these dependencies varies with synchronization mode (in-phase vs. antiphase or 1:1 vs. 2:1; Chen et al., 2001) and with the sensory modality of the metronome (auditory vs. visual; Chen et al., 2002). SMS with visual stimuli (a flashing light) is much more variable than SMS with auditory stimuli (Kolers & Brewster, 1985; Repp & Penel, 2002, 2004), and this is due mainly to increased drift. The $1/f$ spectrum of sequential dependencies is often considered to be the signature of a complex dynamic system, but it could also be the result of a small number of underlying processes operating on different time scales (for recent discussions, see Wagenmakers, Farrell, & Ratcliff, 2004; Wing, Daffertshofer, & Pressing, 2004). Pressing and Jolley-Rogers (1997) have argued that, for asynchronies in SMS, it is actually a predictable consequence of error correction.

5. MODELS OF ERROR CORRECTION

A fundamental point about SMS is that it cannot be sustained without error correction, even if tapping starts without any asynchrony and continues at exactly the right mean tempo. Without error correction, the variability inherent in any periodic motor activity would accumulate from tap to tap, and the probability of large asynchronies would increase steadily (Hary & Moore, 1987a; Voillaume, 1971; Vorberg & Wing, 1996). The inability of even musically trained participants to stay in phase with a *virtual metronome* (i.e., with silent beats extrapolated from a metronome) can be demonstrated easily in the synchronization–continuation paradigm by computing *virtual asynchronies* for the continuation taps. These asynchronies usually get quite large within a few taps, although occasionally, virtual synchrony may be maintained for a while by chance.

There are at least three different theoretical approaches to modeling error correction in SMS. A dynamic systems approach considers the action and the pacing sequence to be a system of weakly (unidirectionally) coupled oscillators that can be described by nonlinear differential equations. The term *error correction* is usually avoided (however, see Engbert, Krampe, Kurths, & Kliegl, 2002, for an exception) in favor of *coupling* or *entrainment*. A control-theoretic approach emphasizes the role of feedback-based regulation and uses engineering vocabulary, together with linear or nonlinear equations. An information-processing approach usually restricts itself to linear models and focuses on specifying the underlying psychological processes, as well as the predicted statistical properties of time series data.[4] Pressing (1998b, 1999) has argued that all of these different approaches can be regarded as variants of a general control equation for referential behavior and, thus, are quite closely related. In particular, the parameter representing coupling strength in nonlinear models corresponds directly to parameter(s) that characterize the effectiveness of error correction in linear models. Linear models are undoubtedly an oversimplification, but they are mathematically more tractable and often provide a good approximation to dynamic systems in the vicinity of stable states.

Early models of error correction in SMS did not distinguish between central (timekeeper) and peripheral (motor) sources of variance or between possible multiple error correction processes. Thus, Michon (1967; Michon & van der Valk, 1967) formulated a simple linear prediction equation that based each ITI on the two preceding IOIs, the main goal being to model the response to IOI perturbations in a pacing sequence (see Section 6). Voillaume (1971) considered the possibility that each asynchrony leads to a correction of the next ITI, although he assumed unrealistically that the correction was as large as the asynchrony. Hary and Moore (1985, 1987a, 1987b) conducted computer simulations of SMS data that led them to formulate a model according to which participants time each tap from either the preceding metronome beat or the preceding tap, randomly alternating between these two referents (i.e., mixed phase resetting). In addition, slow adjustments of the internal time delay of responses (effectively, the timekeeper period) were assumed to occur on the basis of perceived asynchronies, but no allowance was made for possible delays or variability in perception of events. Schulze (1992) subsequently showed that the assumption of mixed phase resetting is formally equivalent to assuming that a proportion α of each asynchrony is corrected on the next tap (see Table 1, sections B and C). This formulation of *phase correction* was adopted in most subsequent modeling studies.

Mates (1994a, 1994b) combined this linear phase correction model with a linear period correction model, according to which the central timekeeper period is adjusted by a proportion β of the difference between the preceding period and the IOI (see Table 1A). The important point of this dual-process error correction model is that phase correction leaves the timekeeper period unchanged. In addition, the model includes perceptual and motor delays that make it possible to account for the NMA. In analogy to the dual sources of variance in the Wing–Kristofferson

Table 1
The Dual-Process Error Correction Model as Usually Stated (A) and the Formal
Equivalence of Linear Phase Correction (B) and Mixed Phase Resetting (C)

A. The Dual-Process Model

$T_n = T_{n-1} - \beta(T_{n-1} - \text{IOI}_{n-1})$	(period correction)	(1)
$a_{n+1} = a_n - \alpha a_n + T_n - \text{IOI}_n$	(phase correction)	(2)

B. Phase Correction Expressed in Terms of Time Points Rather Than Intervals

$a_n = t_n - m_n$	(definition of asynchrony)	(3)
$\text{IOI}_n = m_{n+1} - m_n$	(definition of IOI)	(4)
$t_{n+1} - m_{n+1} = t_n - m_n - \alpha(t_n - m_n) + T_n - m_{n+1} + m_n$	(from 2, 3, and 4)	
$t_{n+1} = t_n - \alpha(t_n - m_n) + T_n$	(phase correction)	(2')

C. Mixed Phase Resetting

$t_{n+1} = t_n + T_n$	(tap-based phase resetting)	(6)
$t_{n+1} = m_n + T_n$	(metronome-based phase resetting)	(7)
$t_{n+1} = (1 - \alpha)(t_n + T_n) + \alpha(m_n + T_n)$	(mixed phase resetting)	(8)
$t_{n+1} = t_n - \alpha(t_n - m_n) + T_n$	(reduction of 8 = 2'; q.e.d.)	

Note—Sources of random noise and delays are omitted here. T_n, expected timekeeper period preceding the nth tap; β, period correction parameter; IOI_n, interonset interval ending with the nth tone; a_n, expected asynchrony between the nth tap and the nth tone; α, phase correction parameter, or relative weight (or probability) of metronome-based phase resetting; t_n, expected time of occurrence of the nth tap; m_n, time of occurrence of the nth metronome tone.

model, phase correction may be considered a relatively more peripheral process than is period correction (Repp, 2001b). Both period correction and phase correction affect the timing of a tap and, thus, change both its asynchrony and its ITI, relative to the previous tap. Some researchers (Thaut & Kenyon, 2003; Thaut, Miller, & Schauer, 1998) have considered the manifest changes in asynchronies and ITIs to constitute phase and period corrections, respectively, although this is not how these processes are defined in Mates's model (for discussions, see Repp, 2001b, 2004a; Thaut & Kenyon, 2004). Repp (2001a) pointed out that the α and β parameters are interchangeable; that is, the two error correction processes are not uniquely identifiable in an SMS task, at least when they are estimated on the basis of trial means. However, with certain assumptions, these parameters can be estimated in a synchronization–continuation paradigm, as will be described in Section 6.3.3.

Pressing (1998a, 1999; Pressing & Jolley-Rogers, 1997) and Vorberg and colleagues (Schulze & Vorberg, 2002; Semjen et al., 2000; Vorberg & Schulze, 2002; Vorberg & Wing, 1996) have independently investigated the detailed implications of a linear phase correction model for the time series structure of asynchronies and ITIs, but without including a period correction component. Instead, they allowed for both first-order and second-order phase correction—that is, compensation for asynchronies occurring either one or two taps back in the sequence. Their model has been applied to data obtained by tapping to isochronous sequences at different tempi, and Pressing (1998a) also investigated different coordination modes. Two salient results are that first-order phase correction (α in Table 1) decreases as the sequence tempo increases, whereas second-order phase correction (represented by a second phase correction term with a separate parameter in the model) emerges only at fast tempi. In dynamic systems terms, the decrease in first-order phase correction with decreases in IOI duration represents a decrease in

coupling strength between perception and action as the frequency increases. Such a change in coupling strength as a function of frequency is well documented in inter-limb coordination (see, e.g., Peper, Beek, & van Wieringen, 1995). Second-order phase correction may reflect the emergence of a binary metrical organization (a form of subjective rhythmicization; Bolton, 1894) in rapid sequences, so that phase correction occurs at two functional levels—beats and subdivisions. This hypothesis predicts that the relative strengths of first- and second-order phase corrections alternate from tap to tap, with second-order phase correction being stronger on beats than on subdivisions—a prediction that needs to be tested.

Most of the model builders initially conjectured that the perceptual detection threshold for asynchronies imposes a limit on phase correction. However, incorporating such a nonlinearity into a model would vastly complicate its mathematics and, therefore, has generally been avoided, with the exception of Mates (1994b), who used computer simulation. Schulze and Vorberg (2002) argued that it may actually be difficult empirically to distinguish models with and without a built-in threshold. Moreover, results of phase perturbation experiments (see Section 6) suggest that phase correction is, in fact, independent of the perceptual detection threshold for either perturbations or asynchronies.

One important theoretical question concerns the nature of the perceptual information on which phase correction and period correction are based. Mates (1994a, 1994b) assumed that phase correction is based on perception of asynchronies, whereas period correction is based on perception of discrepancies between the internal timekeeper period and the sequence IOI duration. However, there are other possibilities. The mixed phase resetting model of Hary and Moore (1985, 1987b) assumes that the perceptual information consists of *time points*, not intervals. Several empirical findings, reviewed in Section 6, tend to favor this hypothesis. Schulze, Cordes, and Vorberg

(2005) recently suggested, on the basis of modeling results, that period correction may, in fact, be based on perception of asynchronies. This issue is clearly not settled yet, and indeed, there may be multiple sources of relevant perceptual information.

In work stretching over 3 decades, Jones and collaborators have developed a dynamic attentional approach to rhythm perception that has culminated in formal models similar to the dual-process model of error correction in SMS (Large & Jones, 1999; McAuley & Jones, 2003). Perceptual experiments often take a perturbation approach (see Section 6)—for example, by requiring participants to detect a phase shift in a tone sequence (see, e.g., Barnes & Jones, 2000). The basic assumption is that fluctuations of attentional energy are entrained by a metronome sequence and that this internal flux of waxing and waning attention (reflecting temporal expectation) is subject to phase correction and period correction in response to perturbations of sequence timing. Thus, rhythm perception is viewed as a form of covert synchronization, and it seems quite likely that the attentional dynamics described in these models are closely linked to the motor system, with motor imagery or simulation of the sensory consequences of rhythmic action accompanying the bursts of attentional energy. If so, rhythm perception may simply be internalized SMS. Further research is needed to determine whether these parallels are really as close as they seem.

6. PERTURBATION STUDIES

The perturbation method was introduced to SMS research by Michon (1967) as a way of investigating the human timing system's response to predictable and unpredictable variation. Perturbations can be global (i.e., affecting every event) or local (restricted to a single event or IOI). Global perturbations are relevant to music perception and performance, because the IOIs in expressive performance are continuously modulated in a more or less predictable fashion (see, e.g., Repp, 1992). In addition to such systematic variations, however, there is always some random variability as well.

6.1. Global Perturbations

When SMS is attempted with a sequence containing unpredictable timing variability, the ITIs tend to echo the pattern of IOIs, resulting in a positive lag 1 cross-correlation (Michon, 1967; Repp, 2002c; Schulze, 1992). This *tracking* behavior can be understood as a direct consequence of phase correction in response to the asynchronies generated by the unpredictable perturbations. Using computer simulation, Hary and Moore (1987a) found evidence of phase correction in response to continuous subliminal (i.e., undetectable) random perturbations, although they did not find a positive lag 1 correlation between ITIs and IOIs, perhaps because the perturbations were so small.

In an interesting recent study, Madison and Merker (2004) introduced binary quasirandom perturbations (governed by a numeric algorithm called a *Kolakoski*

sequence) of various magnitudes in the IOIs of a pacing sequence. There was evidence of tracking for even the smallest (clearly subliminal) perturbations, but variability of asynchronies and ITIs did not increase until the standard deviation of the perturbations approached that of the asynchronies and ITIs. This suggests that tracking of subliminal timing variation merely organizes the existing variability but does not add to it. Furthermore, when the perturbations were large and detectable, they were tracked much less effectively, presumably because the participants chose (and were able) to disregard them.

Given that synchronization is more variable with visual than with auditory sequences—in part, due to less effective phase correction (Repp & Penel, 2002)—it is not surprising that random variations of IOIs are also tracked less well in visual than in auditory sequences (Repp & Penel, 2004).

When global perturbations are detectable and regular, such as a slow sinusoidal modulation of the IOIs, participants are able to reduce their asynchronies by *predicting* upcoming changes (Michon, 1967). The ITIs then show a positive lag 0 correlation with the IOIs. Thaut, Tian, and Azimi-Sadjadi (1998) introduced rapid quasisinusoidal IOI modulation at both subliminal and supraliminal levels but found evidence only of tracking, not of prediction. With a larger modulation amplitude, however, evidence of predictive behavior was found in a later study (Stephan et al., 2002). Prediction probably involves timekeeper period correction. With repeated exposure to a sequence exhibiting a complex but fixed timing pattern, there is a gradual change from tracking to prediction, indicating learning (Repp, 2002c). Such learning may occur, for example, when an accompanist adapts to another musician's expressive timing patterns during rehearsal.

Another form of predictable global perturbation is the gradual acceleration or deceleration of sequence tempo by progressive shortening or lengthening of the IOIs. Michon (1967) used linear changes in IOI duration and found that participants adjusted their ITIs in a stepwise fashion, suggesting that they waited to adjust their internal timekeeper period until a tempo change was detectable and relied on phase correction between period adjustments. This strategy was not evident in other studies, however, in which either very short sequences (Franek, Mates, Radil, Beck, & Pöppel, 1994) or very gradual tempo changes (Madison & Merker, 2005) were used. Data from another recent study (Schulze et al., 2005), however, are suggestive in that regard. Madison and Merker (2005) also found a *rebound* effect in continuation tapping following a tempo change sequence, which suggests that period correction lagged behind the IOI changes in the sequence. Prediction of tempo changes is needed in music performance when a performer is trying to coordinate a lengthy ritardando or accelerando with other players, although tempo changes in music are usually nonlinear in terms of IOI (Repp, 1992; Sundberg & Verrillo, 1980; Todd, 1992). SMS experiments in which more realistic forms of tempo change are used remain to be done.

6.2. Distractor Effects

Distractor effects occur when an unperturbed target sequence, with which participants try to synchronize their taps, is accompanied by an isochronous distractor sequence that is to be ignored. Distractor stimuli seem to engage the phase correction mechanism automatically, often without participants' awareness. When auditory target and distractor sequences (distinguished by pitch) have the same period and their temporal offset (phase relationship) is varied, taps are found to shift in the direction of the distractor tones, especially when the distractor tones precede the target tones (Repp, 2003a, 2004b). Interestingly, this asymmetric attraction (and hence, the phase correction mechanism) is quite insensitive to the magnitude of the pitch difference between the two sequences, but it is affected by a change in the relative amplitude of target and distractor tones (Repp, 2006a).

Repp (2004b) investigated whether the attraction of taps to distractor tones is a function of the absolute temporal separation or of the relative phase between target and distractor tones. The results suggest absolute temporal separation as the determining factor. It appears that tones whose onsets occur within about 120 msec are grouped together and serve as a joint temporal referent in SMS. In other words, both of them engage the phase correction process. The critical interval of ~120 msec is likely to be related to the synchronization threshold for 1:n tapping (Repp, 2003b; see Section 2): When tones in a single sequence occur at rates faster than 8/sec, all of them cease to function as individual referents for phase correction, and this destabilizes SMS.

Repp (2003a) also presented target sequences interleaved with distractor sequences having a slightly different period, so that the temporal separation (and phase relationship) of the target and the distractor tones changed continuously within a trial. This had the effect of periodically modulating the asynchronies between the taps and the target tones, with the taps shifting forward and backward in time, depending on whether the distractor tones had just led or lagged behind the target tones. The effect was again asymmetric, with forward shifts (resulting in more negative asynchronies) being stronger than backward shifts. When the pitch difference between the target and the distractor tones was small and pitch assignments were variable, inadvertent synchronization with the distractor sequence, instead of the target sequence, was common. However, this occurred only rarely when the pitch assignment was held fixed (Repp, 2006a).

The distractor paradigm has also been used in cross-modal SMS experiments to demonstrate the dominance of auditory over visual timing information when the two are in competition (Aschersleben & Bertelson, 2003; Repp & Penel, 2004). Clearly, taps are attracted much more strongly to tones than to flashing lights, and this suggests a difference between the two modalities in relative perceptual weights for phase correction or in the strength of perception–action coupling. Interestingly, auditory dominance was found to be unaffected by a substantial reduction of tone intensity that made the tones subjectively less salient than the lights (Repp & Penel, 2004). This contrasts with findings within the auditory modality, where a distractor sequence can be made more or less distracting by varying its intensity relative to the target sequence (Repp, 2006a).

6.3. Local Perturbations

Local timing perturbations in an isochronous pacing sequence provide a convenient means of probing error correction processes. Averaging across a number of trials containing the same perturbation reduces noise in the data and makes it possible to examine some predictions of error correction models without conducting the detailed analyses of long time series that full evaluation of a statistical or dynamic model requires. Local perturbations are also relevant to music performance: Any timing error, such as may occur during rehearsal or among amateur players, represents a local perturbation to which other players need to adapt if the ensemble performance shall continue in a coordinated fashion.

Three basic types of local perturbation are possible in an isochronous sequence (see Figure 2): (1) a *phase shift* of all tones from a certain point on (i.e., a local change of IOI duration), (2) an *event onset shift* or local phase shift (which results in a compensatory change of two successive IOIs), and (3) a *step (tempo) change*, which is a change in all IOIs from a certain point on (i.e., a local change in the first difference of IOIs). Other possible perturbations would be combinations of these basic types. Note that all three types of perturbation start identically with a local phase shift.

6.3.1. Phase shifts. The adaptive response to phase shifts (Figure 2A) has been investigated in several studies (Repp, 1999b, 2000a, 2001a, 2002a, 2002f). The asynchrony at the point of perturbation necessarily exhibits a shift of opposite sign, after which a return to the baseline (preperturbation) asynchrony generally occurs within a few taps. Given a moderate sequence tempo (IOI = 500 msec in most of the studies summarized here), the adaptation following a phase shift usually takes a roughly exponential time course, as is predicted by a linear first-order phase correction model (Figure 3A). The ITI following the changed sequence IOI changes in the same direction as the perturbation, and subsequent ITIs return to the baseline value, also in exponential fashion (Figure 3B). Note that this adaptation of the ITIs is predicted on the basis of phase correction alone; it is not necessary to assume that period correction occurs following unpredictable phase shifts (although it may occur strategically when phase shifts are predictable and, to a small extent, perhaps even when phase shifts are not predictable; Praamstra, Turgeon, Hesse, Wing, & Perryer, 2003). Positive and negative phase shifts are usually adapted to with equal ease. Remarkably, phase shifts that are well below the perceptual detection threshold are compensated for just as quickly as are detectable phase shifts (Repp, 2000a, 2001a). In fact, the immediate response to large phase shifts is proportionally smaller than that to small phase shifts, which indicates a nonlinearity in the phase error correction process (Repp, 2002a, 2002f).
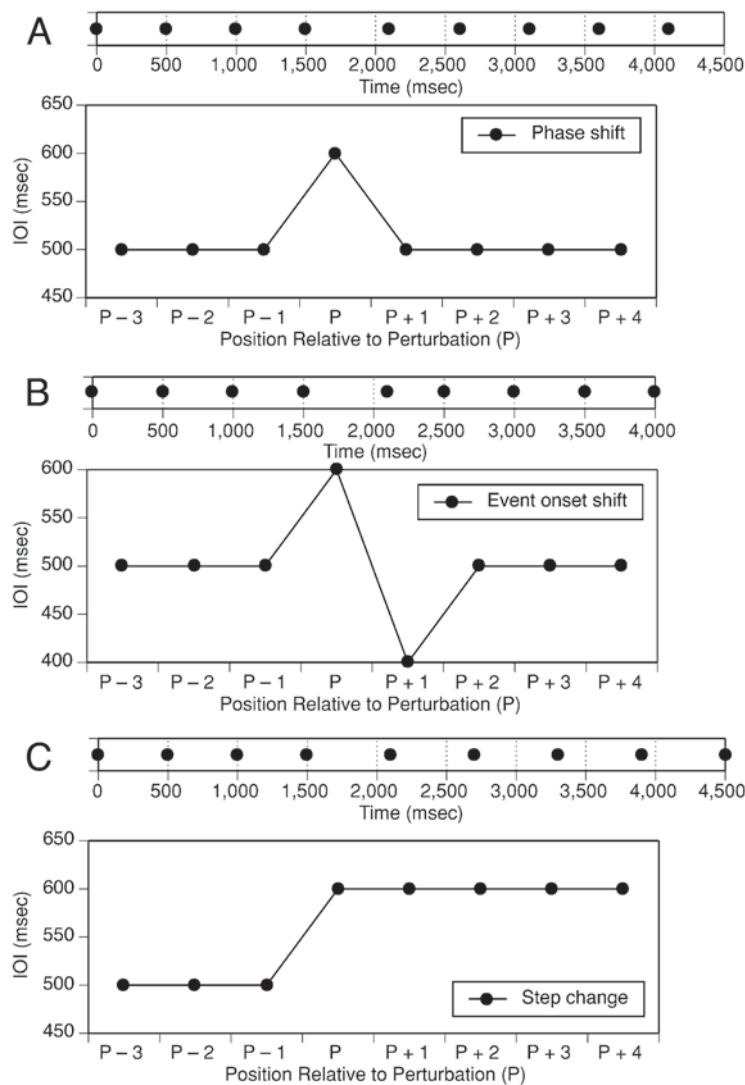
Figure 2. Three types of local perturbation in a metronome sequence. Each panel shows tone onset times above the corresponding interonset interval (IOI) durations. All examples are for a baseline IOI of 500 msec and a perturbation magnitude of +100 msec. From "Automaticity and Voluntary Control of Phase Correction Following Event Onset Shifts in Sensorimotor Synchronization" by B. H. Repp, 2002, *Journal of Experimental Psychology: Human Perception and Performance*, *28*, p. 411. Copyright 2002 by the American Psychological Association. Adapted with permission.

Repp (2000a, 2000b) interpreted the rapid adaptation to subliminal phase shifts as suggesting that action control has direct access to perceptually subliminal timing differences or asynchronies (see Milner & Goodale, 1995). An alternative explanation, however, is provided by mixed phase resetting (Hary & Moore, 1985, 1987a, 1987b; Repp, 2002a, 2004a), which makes the finding much less surprising. In other words, rather than subconsciously perceiving minute interval differences or changes in asynchronies, participants may simply time their next tap, in part, with reference to the phase-shifted tone (phase resetting) and, in part, with reference to the preceding tap.

This hypothesis also explains other findings—for example, why large temporal variability in a context sequence preceding an isochronous test sequence leaves the variability of asynchronies and the adaptive response to phase shifts unaffected, even though it impairs conscious detection of phase shifts (Repp, 2002d), or why amplitude changes that affect interval perception do not affect phase correction (Repp, 2006b). The mixed phase resetting model proposed by Hary and Moore (1985, 1987a, 1987b) thus still has merit as a conceptual framework, despite its formal equivalence to the asynchrony-based phase correction model espoused by other researchers (Table 1).
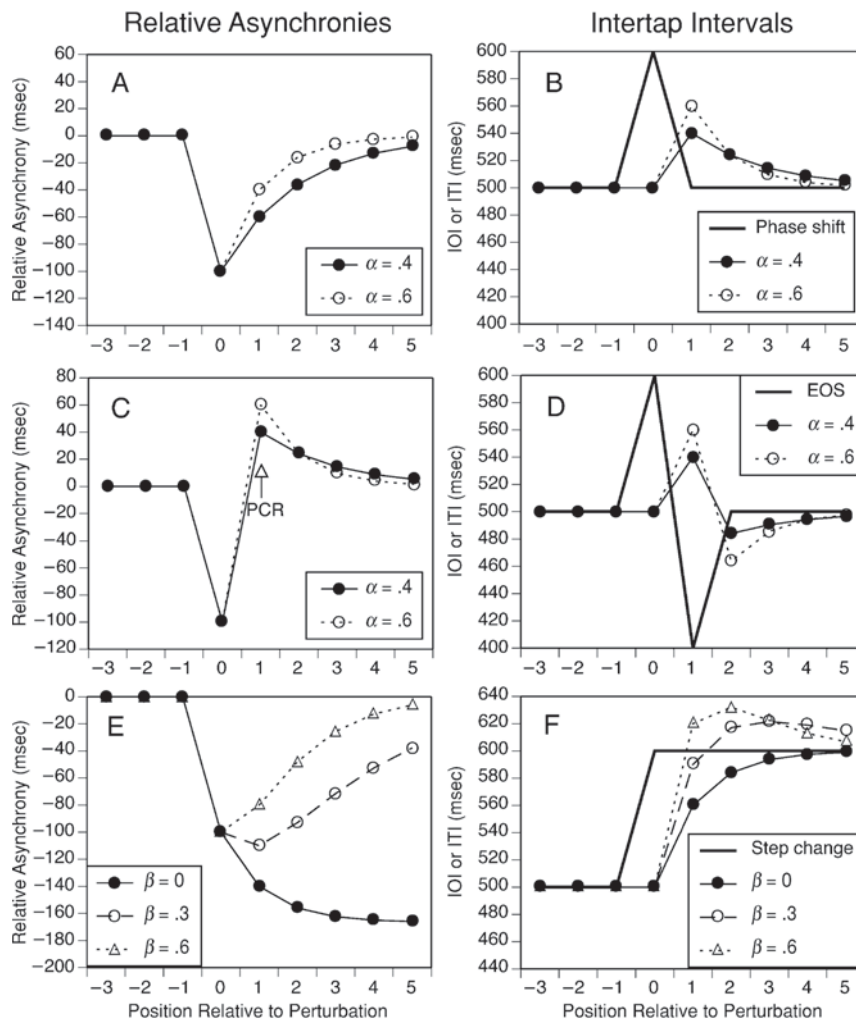
Figure 3. Predictions of the dual-process error correction model (Table 1A): Adaptation of relative asynchronies (i.e., deviations from the mean asynchrony) and intertap intervals (ITIs) to a phase shift (panels A and B), an event onset shift (EOS; panels C and D), and a step change (panels E and F). All examples are for a baseline tone interonset interval (IOI) of 500 msec and a perturbation magnitude of +100 msec. The predictions are for two values of the phase correction parameter α in panels A–D (with $\beta = 0$) and for three values of the period correction parameter β in panels E and F (with $\alpha = .6$). The phase correction response (PCR) is indicated in panel C.

The crucial conceptual distinction is that the phase reset-ting model assumes reliance on *temporal reference points* (tone and tap), whereas the asynchrony-based model assumes reliance on a *temporal interval* (the asynchrony between tone and tap). Actual neural computation of the asynchrony may be necessary only for conscious percep-tion, not for action control—at least, not for phase correc-tion. Rather than randomly alternating, as envisioned by Hary and Moore, the two temporal reference points may be in dynamic competition and simultaneously influence tap timing, with their relative weights depending on a va-riety of contextual factors.

6.3.2. Event onset shifts. Event onset shifts are the most primitive form of perturbation, because they concern a time point, rather than an interval (the first difference between time points) or a difference between intervals. The adaptive response to event onset shifts (Figure 2B) has been investigated in many experiments (Repp, 2002a, 2002c, 2002d, 2002e, 2004c, 2006b; Repp & Penel, 2002). Event onset shifts are theoretically interesting because an adaptive response to them is counterproductive: It leads to an increased asynchrony on the next tap, because that tap coincides with a tone that is not phase shifted (Figure 3C). However, even when participants are instructed to ignore the (unpredictable) perturbation and tap as regularly as they can, they nevertheless exhibit a shift of the follow-ing tap in the same direction as the local phase shift. This shift (i.e., the change in relative asynchrony) of the tap immediately following the perturbation has been dubbed the *phase correction response* (PCR; Repp, 2002a). After

the PCR, the asynchronies of subsequent taps return exponentially to the baseline value. The ITIs track the two IOI changes and then decay exponentially to baseline (Figure 3D).

Although phase correction is largely automatic, participants do have some voluntary control over it, because the unintended PCR to an event onset shift is smaller than the intentional PCR to a phase shift. (This is not reflected in the schematic graphs in Figures 3C and 3A, which are for equal values of α.) This difference is purely a function of participants' intention, because both types of perturbation start with the same local phase shift (Repp, 2002f). The intentional PCR increases monotonically with the magnitude of the perturbation, but the unintentional (involuntary) PCR reaches an asymptote when the magnitude of the perturbation exceeds about 15% of the IOI (Repp, 2002a, 2002f).[5] The unintentional PCR tends to be smaller for negative (forward) than for positive (backward) event onset shifts and, like the adaptive response to phase shifts, occurs even when the perturbation is below the perceptual detection threshold. This is true with both auditory and visual sequences, although the PCR is smaller in the latter case (Repp & Penel, 2002). It is likely that awareness of a perturbation is required to intentionally reduce the PCR, but the data (Repp, 2002f) are somewhat unclear on this point.

Several additional findings obtained with the event onset shift paradigm are explained easily by the mixed phase resetting model, but less so by an asynchrony-based phase correction model. (1) The PCR, whether intentional or not, is about as large in antiphase tapping as it is in in-phase tapping (Repp, 2001a, 2002a). According to an asynchrony-based account, one might expect less effective phase correction in antiphase tapping, because the asynchronies either are very large or must be computed with respect to a virtual event at the midpoint of the IOI (Thaut & Kenyon, 2003). From the phase resetting perspective, there is merely a shorter temporal delay of each tap with respect to the preceding tone. (2) When one or more sequence tones following an event onset shift are omitted, phase correction following the PCR is suspended until the sequence continues (Repp, 2002e). In other words, in the absence of a tone, only the immediately preceding tap can serve as the temporal reference for a tap. Admittedly, this is also what an asynchrony-based model might predict when no asynchrony can be computed. (3) When the tap coinciding with an onset-shifted tone is omitted, or if tapping starts only immediately after the perturbation, the PCR is *larger* than when tapping is uninterrupted, and this is true whether or not the PCR is intentional (Repp, 2001a, 2002a). This is difficult to explain as a consequence of a missing asynchrony, but it follows naturally from the fact that only the perturbed tone is available as a temporal referent for the next tap. (4) When one or more subdivision tones occur between an onset-shifted tone and the next target tone (in 1:*n* tapping), the PCR is reduced even though the asynchrony between the perturbed tone and the previous tap is the same (Repp, 2002a, 2002b, 2004c). It appears that both target tones (beats) and subdivision tones function as temporal referents in a hierarchical metrical

structure (see also Large, Fink, & Kelso, 2002). (5) In accord with this interpretation, perturbation of a subdivision tone from its expected temporal position results in an involuntary PCR, even though it is not associated with an asynchrony (Repp, 2002a, 2002b, 2004c). (6) Finally, increasing or decreasing the intensity of a shifted tone affects perceptual judgments of temporal regularity but has no systematic effect on the PCR, which suggests that perception concerns intervals, whereas phase correction is based on stimulus onsets (Repp, 2006b).

A small involuntary PCR is also elicited by a single distractor tone occurring in the vicinity of a target tone (Repp, 2003a). If the distractor tone is close to the target tone, the PCR is about half as large as if the target tone itself had been shifted, which suggests that both tones serve as temporal references (perhaps as an integrated unit). The pitch difference between target and distractor tones seems to make little difference, and target and distractor tones can, in fact, be interchanged without affecting the PCR.

6.3.3. Step changes. Phase shifts and event onset shifts perturb the sequence tempo only locally and, therefore, are unlikely to elicit significant period correction, at least as long as the perturbations occur unexpectedly and no tempo change is expected to follow the initial phase shift. (For an experiment in which both phase shifts and step changes were employed within the same design, see Large et al., 2002.) The step change perturbation (Figure 2C) is designed to engage period correction, as well as phase correction. Michon (1967) introduced fairly large, easily detectable step changes in IOI duration and found that the subsequent ITIs exhibited considerable *overshoot* (i.e., exceeded the new sequence IOI duration) before approaching the new IOI duration (see Figure 3F; $\beta = .6$). Hary and Moore (1985) introduced very small, subliminal step changes and did not report any ITI overshoot; they concluded from computer simulations that (their model's equivalent of) period correction was very slow and gradual. Thaut, Miller, and Schauer (1998) employed three magnitudes of step change that straddled the detection threshold. They observed different patterns of adaptation to large and small changes: Although ITIs adapted fairly rapidly in both cases, overshoot occurred only after large, detectable changes. Asynchronies also exhibited different patterns, adapting rapidly after large step changes but only very gradually after small step changes. Very similar results were obtained in an antiphase tapping study by Thaut and Kenyon (2003).

Repp's (2001b, 2004a) interpretation of these data is different from that given by Thaut and colleagues, which remains on the descriptive level of observable phase (= asynchrony) and period (= ITI) adaptation. Phase and period correction, as conceptualized in Mates's (1994a, 1994b) dual-process model, are hypothetical internal processes that underlie the observable adaptations.[6] Because (as was mentioned in Section 5) these internal processes are not uniquely identifiable during SMS, as long as only averaged data are analyzed, Repp (2001a, 2001b; Repp & Keller, 2004) employed a synchronization–continuation paradigm to estimate period correction. A pacing se-

quence was terminated at variable distances after a step change, and the participants were instructed to synchronize with the sequence and then to continue tapping at its final tempo. The mean ITI of the continuation tapping was taken as an estimate of the final sequence tempo (i.e., of the internal timekeeper period at the end of the sequence). From this estimate, it could be determined how far period correction had progressed between the step change and the end of the sequence. Period correction was found to be minimal after a single changed IOI and to increase gradually as a function of the number of changed IOIs, up to about five (Repp, 2001a, 2001b). Importantly, it depended also on whether or not a tempo change had been detected, with period correction being slower for undetected than for detected changes, even when they were of the same magnitude (Repp, 2001b; Repp & Keller, 2004). This led to the conclusion that phase correction is rapid and automatic, whereas period correction is at least in part dependent on awareness of a tempo change.

The dual-process model of error correction predicts the pattern of data obtained in the studies just reviewed. When a step change is detected ($\beta > 0$), the simultaneous engagement of both phase and period correction leads to the observed initial ITI overshoot (Figure 3F; $\beta = .3$ and .6), whereas failure to detect a step change engages primarily phase correction, resulting in ITI adaptation without overshoot (Figure 3F; $\beta = 0$). It is important to realize that ITI adaptation can occur in SMS even if there is no period correction at all. This is not true for the asynchronies: If there is no period correction, they do not adapt but, rather, converge on a value that diverges from the mean asynchrony by more than the size of the step change (Figure 3E; $\beta = 0$). The more period correction is engaged, the faster the asynchronies adapt (Figure 3E; $\beta = .3$ and .6). Thus, it seems to be the mismatch between the internal timekeeper period and the IOI (a form of detuning; see Section 3) that leads to the observable phase discrepancy.

Using a dual-task paradigm in combination with the synchronization–continuation tapping task, Repp and Keller (2004) showed that period correction not only is dependent on awareness of a tempo change, but also is sensitive to the attentional requirements of the task, whereas phase correction is not. Moreover, when the participants were instructed not to react to a step change and to keep tapping at the *initial* sequence tempo, they were able to suppress period correction completely, but not phase correction. These results confirmed that period correction is, at least in part, a higher level cognitive function, whereas phase correction is mainly a lower level automatic process. Intentional period modulation is likely to be the process that underlies the prediction and production of all kinds of quasiperiodic timing patterns, such as expressive timing in music (Repp, 2002c). By contrast, phase correction is purely reactive and specific to SMS.

One obvious situation in which period correction is important, not yet mentioned, is beginning to synchronize with a sequence, especially when its tempo is not known in advance. Fraisse (1966) observed that about three taps

are needed to *tune in* to a sequence if tapping starts immediately after the first tone. This tuning-in clearly requires period correction, perhaps better called *period setting* in this context. If tapping begins later in the sequence, however, the period is set during listening, and tapping starts accurately. Repp (2001a) found that the time of occurrence of the first tap (following the first tone) is a function of both the preceding sequence tempo and the mean tempo of the sequences in an experiment. Interestingly, an initial tuning-in is observed even when all sequences have the same tempo (see, e.g., Repp, 1999b), with the first tap usually occurring too late (at least with an IOI of 500 msec). For a detailed study of the tuning-in process, see Semjen, Vorberg, and Schulze (1998), who used a unique *continuation–synchronization* paradigm in which the pacing sequence started during self-paced tapping.

7. NEURAL CORRELATES OF SMS[7]

There has been a veritable explosion of neuroscience research in recent years, and many studies of timing and motor control, including SMS, have been published. It is impossible to do justice to the complexity of this research within the space available here. For a recent review of studies of brain function in timing more generally, see Wing (2002). The two brain structures mentioned most often in connection with timing are the basal ganglia and the cerebellum, each of which has many reciprocal connections with cortical areas (Middleton & Strick, 2000). A cerebellar–cortical loop is likely to be involved in SMS, because the cerebellum has been shown to be important not only for movement timing (Ivry, 1997; Ivry, Keele, & Diener, 1988; Penhune, Zatorre, & Evans, 1998), but also, more generally, for feedback-based learning (Doya, 1999), temporal prediction (Tesche & Karhu, 2000), and internal modeling of sensorimotor dynamics (Miall & Reckess, 2002; Wolpert, Miall, & Kawato, 1998).

Rao et al. (1997) conducted an fMRI study in which they compared synchronization and continuation tapping and found that self-paced tapping engaged neural systems, in addition to the sensorimotor areas activated during SMS. These additional areas were interpreted as being concerned with explicit timing and auditory sensory memory. Gerloff et al. (1998) examined the activation and functional coupling of different brain areas during metronome-paced and self-paced finger extensions by means of spectral power and coherence analyses of EEG recordings. They, too, found that self-pacing led to increased activation of some brain areas, such as the contralateral sensorimotor cortex and the supplementary motor area, as well as increased coherence between the relevant brain areas. Lewis, Wing, Pope, Praamstra, and Miall (2004) also found greater activity in the supplementary motor area and the basal ganglia during continuation tapping than during SMS. Thus, tapping without a metronome actually seems to be a more demanding task than is SMS. However, fMRI studies by Jäncke, Loose, Lutz, Specht, and Shah (2000) and Jantzen, Steinberg, and

Kelso (2004) showed similar brain activation patterns for synchronization and continuation tapping with auditory stimuli.

The main result of Jäncke et al. (2000) was that SMS with auditory and visual pacing sequences activated different areas in the cerebellum, one associated with motor control and the other more with perception and timing of complex sequences. They concluded that SMS with auditory sequences elicits an *internal movement rhythm*, whereas SMS with visual sequences does not. This seems consistent with the auditory dominance observed in audio-visual SMS studies (Aschersleben & Bertelson, 2003; Repp & Penel, 2002, 2004; see Section 6.2).

Lewis et al. (2004) asked participants to synchronize with auditory rhythms of different complexity and looked for brain areas whose activity increased with rhythmic complexity. These areas included the bilateral supplementary motor area, parts of the premotor cortex, the right dorsolateral prefrontal cortex, and the right primary motor cortex. The authors hypothesized that the prefrontal cortex is involved in error monitoring or correction. None of these areas showed a correlation with rhythm complexity during self-paced continuation tapping of the various rhythms.

A series of studies conducted by Kelso and colleagues has been concerned with the difference between in-phase and antiphase SMS and with the phase transition from the latter to the former when the sequence tempo is increased. The movement was usually finger flexion or squeezing of an air pillow, not tapping on a surface. Using EEG (Mayville, Bressler, Fuchs, & Kelso, 1999), MEG (Chen, Ding, & Kelso, 2003; Kelso et al., 1998; Mayville et al., 2001), and fMRI (Jantzen, Steinberg, & Kelso, 2002, 2004; Mayville, Jantzen, Fuchs, Steinberg, & Kelso, 2002), these researchers consistently have found substantial differences in brain activity between the two coordination modes. Mayville et al. (2002) made the intriguing suggestion that antiphase coordination is "organized on a cycle-by-cycle basis" (i.e., based on continuous phase resetting), whereas in-phase coordination is more continuous and automatic. Areas showing increased activity during antiphase coordination included the premotor cortex, the basal ganglia, and the cerebellum. However, differences between the coordination modes diminished with practice (Jantzen et al., 2002). Later, Jantzen et al. (2004) found that self-paced continuation tapping following in-phase or antiphase SMS showed the same differences in brain activation (measured with fMRI) as the two synchronization modes. This may have been due to the maintenance of different cognitive frameworks during continuation tapping.

Several studies may be of crucial importance for understanding the neural basis of the synchronization threshold (~120 msec) discussed in Section 2. Carver, Fuchs, Jantzen, and Kelso (2002) demonstrated that the first large MEG response to auditory stimulation, a negativity with a latency of about 100 msec, vanishes when the IOIs between stimuli approach 100–160 msec. The resulting steady-state response to a rapid train of stimuli may be the neural correlate of obligatory perceptual grouping and the loss of event individuality. In another MEG study, Pollok, Gross, Müller, Aschersleben, and Schnitzler (2005) analyzed coherence patterns within the brain during SMS with an auditory pacing sequence and found that "the prevailing frequency of cerebrocerebral coupling was between 8 and 12 Hz" (p. 648). In a third MEG study, Gross et al. (2002) recorded self-paced and visually paced finger flexion movements and found kinematic discontinuities, believed to represent intermittent output from motor areas of the brain, that occurred at an average frequency of 8 Hz and corresponded to coherent oscillatory activity in a cerebello–thalamo–cortical loop at roughly the same frequency. These findings suggest that an interval of about 125 msec represents a critical temporal limit not only of perception, but also of motor control.

The NMA in the standard in-phase tapping task (see Section 3) was examined in a MEG study by Müller et al. (2000). Evoked brain responses were averaged after time locking them to either click onsets or tap onsets. Three different brain sources were inferred, one in the motor cortex and two in the sensorimotor cortex. Two of these were related to tap onset, but the third appeared to be related to whichever event occurred later. This third source, in the inferior sensorimotor cortex, was interpreted as being related to the evaluation of asynchronies on the basis of sensory feedback. This interpretation was not supported, however, by later MEG studies (Pollok et al., 2003, 2004), which replicated the basic finding of three cortical sources but showed the inferior sensorimotor source to be related primarily to the tap, probably just reflecting registration of somatosensory feedback.

It seems reasonable to hypothesize that phase correction and period correction in SMS are associated with different brain circuits. Middleton and Strick (2000) reviewed evidence for distinct neural loops between the basal ganglia and the cerebellum, on the one hand, and the motor cortex and the prefrontal cortex, on the other hand, which subserve motor control and more cognitive functions, respectively. Lewis and Miall (2003a, 2003b) drew a perhaps related distinction between brain circuits for the timing of short (more automatic) and long (more cognitive) intervals. Kubovy and Van Valkenburg (2001) considered emerging evidence for parallel auditory processing streams analogous to the dorsal and ventral streams in vision, which subserve action control and conscious perception, respectively (Milner & Goodale, 1995; Norman, 2002). From that perspective, phase correction seems very much a dorsal function, and period correction a ventral one.

Rao et al. (1997), in an fMRI study, noted that the dorsolateral prefrontal cortex, which is known to be involved in higher level cognitive functions and working memory, was not activated during SMS with a metronome. However, a PET study by Stephan et al. (2002) demonstrated prefrontal cortex activity during SMS with temporally modulated sequences. They presented periodic IOI modulations of three different magnitudes (as in Thaut, Tian, & Azimi-Sadjadi, 1998). The smallest modulations were generally not detected and led to tracking behavior. The

largest modulations were detectable and yielded predictive tapping behavior. A corresponding change of brain activity from the orbitofrontal and ventral prefrontal cortex to the (mostly right) dorsolateral prefrontal cortex was observed. The former areas thus appeared to be involved in subconscious tracking, but the latter in conscious prediction. Although these findings were not interpreted within the framework of Mates's (1994a, 1994b) dual-process model of error correction, they are consistent with the hypothesis (Repp & Keller, 2004) that period correction, which most likely is responsible for prediction, is a higher level cognitive process. However, because the study did not include control conditions without tapping, it is not clear to what extent the observed activations were due to motor timing control, rather than just to perception of perturbations.

An EEG study by Praamstra et al. (2003), in which a phase shift paradigm (Repp, 2000a) was used, yielded results suggestive of a neural dissociation of phase correction and period correction. (It appears that some period correction was elicited by the phase shifts because they occurred at regular intervals and, thus, were somewhat predictable.) That phase correction involves the cerebellum is suggested by an fMRI study by Lutz, Specht, Shah, and Jäncke (2000), in which finger taps were paced with regular or irregular visual stimuli. In the irregular condition, there was increased activation in contralateral thalamic and ipsilateral cerebellar nuclei, which Lutz et al. attributed to increased error correction. A study by Molinari, Leggio, De Martin, Cerasa, and Thaut (2003), however, casts doubt on a crucial role of the cerebellum in error correction: Patients with cerebellar atrophy or lesions performed just like normal controls in their adaptive response to small and large step changes (as in Thaut, Miller, & Schauer, 1998; see Section 6.3.3). In particular, they showed ITI overshoot following large step changes, which has been interpreted as the simultaneous operation of phase and period correction (Repp, 2001b). Thus, both of these processes seemed to be intact. However, the patients showed larger variability than did the controls, which does suggest a possible impairment of phase correction, as well as impaired perception of tempo changes. Molinari et al. suggested that motor entrainment by auditory stimuli can occur by direct communication between auditory and motor neurons—an intriguing hypothesis that calls for further research.

Despite a considerable number of studies, the neuroscience of SMS is still in its beginnings and does not yet yield a very coherent picture. In particular, there is as yet no clear support for distinct neural substrates for phase correction and period correction. However, a detailed understanding of the neural systems underlying SMS can be expected to be gained in the coming years.

8. SMS IN MUSICAL CONTEXTS[8]

Considering the importance of SMS in music performance and dance, it is surprising how little research has been done with materials or actions that approach the complexity of real music. Most of the relevant studies represent only modest advances beyond the standard tapping tasks. Moreover, the role of auditory feedback has usually been downplayed in SMS (with the exception of a few studies in which it has been explicitly manipulated; see Section 3), whereas in music performance, the production of sound is the ultimate goal of movement.

Isochronous tapping is frequently used as a way of determining the period and phase of the perceived metrical beat(s) in rhythmic patterns or in music (see, e.g., Drake, Jones, & Baruch, 2000; Drake, Penel, & Bigand, 2000; Handel & Lawson, 1983; Handel & Oshinsky, 1981; Jones & Pfordresher, 1997; Oshinsky & Handel, 1978; Parncutt, 1994; Snyder & Krumhansl, 2001; Toiviainen & Snyder, 2003; van Noorden & Moelants, 1999; Vos, van Dijk, & Schomaker, 1994). However, these beat-finding studies have usually been concerned only with the approximate position of the taps, not with synchronization accuracy or error correction; therefore, they are somewhat outside the scope of this review. One of the most detailed sets of such data (Snyder & Krumhansl, 2001) formed the basis of a successful computer modeling effort by Large (2000). It is noteworthy that generally, no NMA has been found in studies in which rhythmically complex materials have been employed (e.g., Snyder & Krumhansl, 2001; Thaut et al., 1997; Toiviainen & Snyder, 2003), which is consistent with the perceptual hypothesis of Wohlschläger and Koch (2000; see Section 3).

The task in beat-finding studies is generally to tap in phase with the perceived beat, which is induced by various properties of the music. When a beat is difficult to perceive, synchronization is less accurate or unsuccessful (Patel et al., 2005). The same rhythm often can be conceived within different metrical frameworks that not only may be induced by the preceding context, but also can be imposed at will to some extent—for example, when prompted by musical notation (Repp, 2005b, 2005d). Visual rhythms do not seem to induce the feeling of a beat (Patel et al., 2005), one reason being that they include IOIs that are shorter than the visual synchronization threshold (see Section 2).

When participants are required to tap with every tone of a slow isochronous musical excerpt that is performed metronomically under computer control, their taps have been found to exhibit systematic deviations from isochrony (Repp, 1999a, 1999c, 2002c). The deviations are small but emerge clearly when asynchronies and ITIs are averaged across a number of trials and participants, so that random variation is reduced. Thus, it appears that some aspects of musical structure have an involuntary influence on the precise timing of the coordinated movements. The timing of the taps is not very similar to expressive performance timing, which primarily reflects the melodic–rhythmic grouping structure, but seems to be related to the metrical structure of the music (see also Keller & Repp, 2005). Nevertheless, Repp (2002c) showed that synchronization with expressively timed music is easier than synchronization with a monotone sequence that has the same timing pattern or with music that has an atypical or structurally

inappropriate (phase-shifted) expressive timing pattern. Thus, knowledge of the musical structure helps predict expressive timing variation.

A recent study in which participants tapped repeated cycles of *uneven* rhythms, such as 2:3 or 2:2:3, at various tempi while being paced either by a simple metronome or by a precise rhythm template (Repp et al., 2005) provided interesting information about how a rhythm is aligned with pacing tones. The 2:3 ratios in these rhythms were characteristically distorted in the direction of 1:2, especially at fast tempi. This implies increased asynchronies between taps and a precise rhythmic template. When synchronizing with such a template, participants generally tapped in a way that minimized the average asynchrony per rhythm cycle, rather than minimizing the asynchrony of the metrical downbeat, whose location distinguished rhythms such as 2:3 and 3:2. However, when the pacing sequence was a simple metronome whose beats were to be aligned with the metrical downbeat of the tapped rhythm, the asynchronies were quite different from those obtained for the downbeat taps during synchronization with a rhythm template. In other words, the temporal alignment of a rhythm with a pacing sequence depends on which, and how many, taps have corresponding pacing tones. The alignment is evidently a consequence of phase correction, which can operate only when a pacing tone is present.

Franek, Radil, and Indra (1988) likewise found that participants could not synchronize accurately with cyclically repeated rhythms when they embodied complex interval ratios. In various other studies (e.g., Semjen & Ivry, 2001; Semjen & Vos, 2002), a metronome has been used to pace rhythm production, but these studies have focused mainly on bimanual interactions.

There seems to be only one study in the literature in which a task familiar to many musicians—namely, playing music in synchrony with a metronome—has been examined. Repp (1999c) asked pianists to play two complete Chopin preludes in that fashion and compared the results with those for playing in strict time (metronomically) without a metronome. The main difference was that the correlation between successive interbeat intervals (the lag 1 autocorrelation) was negative when the participants played with a metronome but was positive when they played merely in strict time. Although the Wing–Kristofferson model predicts a negative lag 1 autocorrelation for self-paced timing, intended *metronomic* performances of music typically retain vestiges of expressive timing, which leads to a positive lag 1 autocorrelation (see also Penel & Drake, 1998, 2004; Repp, 1999a). During synchronization with a metronome, however, phase correction appears to shift that correlation in the negative direction. Although the timing of beats in these performances was much more regular than in normal expressive performance, the timing of key depressions between beats (i.e., of rhythmic subdivisions) showed large deviations from regularity, just as in expressive performance. Thus, regularity at one metrical level does not imply regularity at a lower level.

Synchronization of music performance with a conductor's movements has not yet been investigated in great detail, although preliminary work has been reported (Luck, 2002). This is a potentially very interesting research area with important practical implications.

Clearly, the most fruitful and rewarding application of synchronization skills is to perform music in an ensemble. 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 msec. As one should expect, asynchronization was lower at fast than at slow tempi. Using the same measure, Shaffer (1984) examined the coordination between two pianists in duet playing and found asynchronization similar to that reported by Rasch, despite considerable expressive timing variation. Evidently, the pianists were able to predict each other's expressive timing to a considerable extent. It should be noted that in both studies, the musicians were also able to use visual cues for coordination. A recent study (Keller, Knoblich, & Repp, in press) investigated the asynchronies generated by pianists playing duets with recorded performances, when visual cues were not available. The hypothesis of that study was that the pianists would be more accurate synchronizing with performances recorded by themselves than with those recorded by other pianists. This was indeed the case, although the difference was relatively small. For some observations on ensemble timing in jazz performance, see Friberg and Sundström (2002), and Schögler (1999/2000).

Ensemble playing requires not only in-phase synchronization with other players, but also precise alternation (antiphase coordination) and other, more complex forms of rhythmic coordination. Keller (1999, 2001; Keller & Burnham, 2005) required listeners to attend to and later recognize one or both parts of a multipart rhythmic pattern, and in one experiment, percussionists had to produce a memorized rhythm concurrently with a different, computer-controlled rhythm. However, synchronization accuracy was assessed only in a qualitative way. The focus in these studies was on *prioritized integrative attending* (i.e., attending to one's own part, as well as to the integrated rhythm of several parts) and on the role of metrical structure. Nevertheless, they serve as a model of the degree of sophistication and ecological validity that is needed to close the gap between laboratory SMS research and actual music performance.

9. CONCLUSIONS

Research on SMS is a relatively small and circumscribed field, although it is closely related to research on perception–action relationships, rhythmic skills, bimanual coordination, and music performance. Most of the studies reviewed here appeared within the last 10 years. Three major areas of focus can be distinguished: research

on the NMA, mathematical modeling or computer simulation, and behavioral studies of error correction using the perturbation method. One important outcome of this research has been the evidence suggesting the existence of two error correction processes, one being largely automatic and operating via phase resetting, and the other being mostly under cognitive control and, presumably, operating via a modulation of the period of an internal timekeeper. Although there may be alternative ways of conceptualizing this dichotomy, the dichotomy itself seems to be a robust finding and is closely related to the distinction between mostly subconscious *dorsal* processes for action control and *ventral* processes for conscious perception and decision making (Kubovy & Van Valkenburg, 2001; Milner & Goodale, 1995; Norman, 2002). In this general sense, then, research on auditory SMS can be seen to be a legitimate branch of research on perception and action, and one focusing mainly on the auditory modality, in contrast to most other perception–action research that is being conducted in the visual domain—typically, "where the action is" in psychology.

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NOTES

1. Some researchers distinguish synchronization (in-phase) from syncopation (antiphase). Here, however, SMS is considered to include all forms of rhythmic coordination, regardless of phase relationship.

2. When the tap precedes the stimulus onset, the asynchrony is negative by convention. The term *negative mean asynchrony* is used here (instead of just *negative asynchrony*) to acknowledge that, because of inevitable variability, some individual asynchronies may, in fact, be positive. Each asynchrony is computed between two time points—respectively, the physical event onset and the time of occurrence of the action, which for a tap is the time of contact with a surface. (For some events or actions, the onset time is not obvious, and a criterion needs to be specified.) Dynamic systems theorists prefer the continuous measure of relative phase, which in the discrete case amounts to the asynchrony divided by the IOI. A relative measure of synchronization accuracy is preferable in some research contexts, an absolute measure in others.

3. Whether it is the variance or the standard deviation that varies proportionally with the ITI is a matter of contention in the literature. In most data sets, the two alternatives are difficult to distinguish.

4. A fourth approach might be considered purely formal and atheoretical (see, e.g., Hasan & Thaut, 1999).

5. This result was obtained with an IOI of 500 msec. A wider range of IOIs needs to be investigated.

6. The terminological convention of referring to observable effects as *adaptation* and to internal processes as *correction*, proposed by Repp (2004a), is by no means followed consistently in the literature.

7. Abbreviations used in this section: EEG (electroencephalography), MEG (magnetoencephalography), PET (positron emission tomography), and fMRI (functional magnetic resonance imaging).

8. For a more detailed review than that given in this section, see Repp (in press).