

Control of Expressive and Metronomic Timing in Pianists

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ABSTRACT. In 12 tasks, each including 10 repetitions, 6 skilled pianists performed or responded to a musical excerpt. In the first 6 tasks, expressive timing was required; in the last 6 tasks, metronomic timing. The pianists first played the music on a digital piano (Tasks 1 and 7), then played it without auditory feedback (Tasks 2 and 8), then tapped on a response key in synchrony with one of their own performances (Tasks 3 and 9), with an imagined performance (Tasks 4 and 10), with a computer-generated performance (Tasks 5 and 11), and with a computer-generated sequence of clicks (Tasks 6 and 12). The results demonstrated that pianists are capable of generating the expressive timing pattern of their performance in the absence of auditory and kinaesthetic (piano keyboard) feedback. They can also synchronize their finger taps quite well with expressively timed music or clicks (while imagining the music), although they tend to underestimate long interonset intervals and to compensate on the following tap. Expressive timing is thus shown to be generated from an internal representation of the music. In metronomic performance, residual expressive timing effects were evident. Those did not depend on auditory feedback, but they were much reduced or absent when kinaesthetic feedback from the piano keyboard was eliminated. Thus, they seemed to arise from the pianist's physical interaction with the instrument. Systematic timing patterns related to expressive timing were also observed in synchronization with a metronomic computer performance and even in synchronization with metronomic clicks. These results shed light on intentional and unintentional, structurally governed processes of timing control in music performance.

Key words: expression, feedback, musical imagery, music performance, synchronization, timing

Psychologists interested in timing mechanisms and motor control have often employed finger-tapping tasks, requiring participants either to tap in synchrony with an isochronous stimulus sequence (e.g., Hary & Moore, 1987; Mates, 1994a, 1994b; Michon, 1967; Woodrow, 1932) or to tap freely at a prescribed or self-chosen constant rate (e.g., Collyer, Broadbent, & Church, 1992, 1994; Ivry & Hazeltine, 1995; Wing & Kristofferson, 1973). If the rate is

changed, that is done between trials. One well-known result is that variability increases with intertap interval duration (above 300 ms) in both kinds of tasks. The standard deviation tends to be a linear function of interval duration between about 300–1,000 ms (Collyer, Boatright-Horowitz, & Hooper, 1997; Peters, 1989), and the coefficient of variation is typically 3–4%, so Weber's law holds approximately. Variability increases disproportionately outside that range. Wing and Kristofferson have devised methods for separating two sources of variance, one attributable to a central timekeeper and the other arising from peripheral motor processes, and considerable attention has been given to modeling the error correction process that enables a tapper to maintain synchrony with an external or internal pacing stimulus (Hary & Moore, 1987; Mates, 1994a, 1994b; Michon, 1967; Schulze, 1992; Vorberg & Wing, 1996).

Some researchers have studied timing accuracy in piano performance from a motor control perspective, focusing on the even playing of scales. Thus, Wagner (1971) found that the variability of inter-keystroke intervals in professional pianists was minimal at rates of 6–9/s and increased at both faster and slower rates. Although the variability at slow tempi seemed random, at fast tempi variability was systematic and was derived from fingering patterns. In Wagner's study, the minimal variability occurred at shorter interonset intervals (IOIs) than in typical finger-tapping studies; that difference may have been caused partly by the use of different fingers for successive keystrokes and partly by the musicians' high level of skill. MacKenzie and Van Eerd (1990), in a study of less proficient pianists (their variability was about twice as large as that of Wagner's pianists),

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found minimal standard deviations at rates of 4–6/s and an increase at faster rates, again caused by systematic fingering patterns. Those timing patterns were not intended by the pianists but, rather, were the consequence of automatic motor routines and biomechanical constraints.

In all those studies, the participants' aim was to produce a rhythmically uniform sequence of actions. That pattern is not typical of expressive music performance, however, where intentional deviations from mechanical regularity are the rule. Such deviations can be observed most clearly in slow, expressive pieces in which motor automatisms and biomechanical constraints do not play a significant role. In many studies, expressive timing patterns have been found to be highly replicable across repeated performances and to be closely related to the musical structure, especially the hierarchical phrase (grouping) structure (Gabrielsson, 1987; Palmer, 1989; Povel, 1977; Repp, 1992, 1995; Seashore, 1938; Todd, 1985). Thus, those intentional patterns must be mentally represented in some form and must be controlled by a flexible timekeeping mechanism.

Detailed studies of pianists' expressive timing from a motor control perspective have been conducted by Henry Shaffer and his colleagues (Clarke, 1982; Shaffer, 1980, 1981, 1984; Shaffer, Clarke, & Todd, 1985). The theoretical account emerging from those studies is that performers use a structural representation of the music to construct a timing schedule that is executed under the control of a flexible central timekeeper. When smaller rhythmic groups are nested within larger metrical units, they may be executed by flexible motor procedures (Shaffer et al., 1985). To account for musicians' ability to maintain a basic tempo and to reproduce the tempo of an earlier performance, an additional "more stable referent" (Shaffer, 1981, p. 370) seems to be needed. Epstein (1995) has suggested that this stable referent takes the form of a rigid timekeeper (a "ground beat") operating in parallel with the flexible timing control. There are problems with that theory, however (see Repp, 1996), and a form of absolute interval or tempo memory (Ivry & Hazeltine, 1995; Keele, Nicoletti, Ivry, & Pokorny, 1989; Levitin & Cook, 1996) seems a more plausible basis for tempo stability.

In rhythmically uniform production tasks, variability can be assessed within trials because all successive IOIs are intended to be the same. One can use autocorrelation techniques to examine compensatory adjustments between adjacent IOIs (Hary & Moore, 1987; Mates, 1994a, 1994b; Vorberg & Hambuch, 1978). In expressive performances, on the other hand, most of the variability in IOI durations is intended, although the precise intended IOI durations are not known. Therefore, unintended variability can be assessed only across repeated performances of the same music by the same artist, provided he or she is instructed to hold the expressive intentions constant. One question of considerable interest with regard to the underlying timing mechanisms is whether the standard deviation of the IOIs increases with their intended duration (estimated as their average duration across a number of repetitions), as it does

in the production of uniform rhythms. Shaffer et al. (1985) addressed that question obliquely by examining the Weber fractions (coefficients of variation) for the IOIs in a short passage of piano music by Satie, played nine times by a well-known concert pianist. Repp (1997b) calculated standard deviations from their data and found that they increased with IOI duration in an approximately linear fashion. He subsequently replicated that finding in a larger data base comprising triple performances by 10 advanced student pianists of two complete piano pieces by Schumann and Debussy. The increase in variability was also evident when the IOI durations were normalized to a common nominal note value so that differences in IOI duration were caused by expressive timing alone. Although the Weber fraction was not constant and short IOIs exhibited a wide range of standard deviations, the data clearly indicated that precision of expressive timing decreases as IOI duration increases. Moreover, in the relatively slow music examined, there was no evidence for hierarchical timing control in the form of negative covariation among adjacent IOIs.

The previous results provided the background for the present study, in which pianists' timing patterns and timing precision were examined in 12 tasks, each of which comprised 10 trials. One of my purposes for using the first 6 tasks was to determine to what extent the pattern and precision of expressive timing depend on auditory feedback and on carrying out manual actions on the piano keyboard. If expressive timing is generated from an internal representation of the musical structure, then it should be possible to produce its pattern without actually hearing the music and even without interacting with a musical instrument. In other words, expressive timing should arise purely from the musical imagination (or *audiation*, as Gordon, 1993, has called it). Moreover, such real-time imagery should also enable a pianist to predict and synchronize with the timing of a stimulus sequence that mimics the expressive timing of the music imagined. In the first 6 tasks, then, I attempted to show that expressive timing can be represented in the musical imagination. The remaining 6 tasks were concerned with situations in which a pianist does not intend to produce expressive timing but rather tries to time his or her actions metronomically. Here, one may observe unintended but systematic deviations from regularity that are induced by the musical structure heard or imagined. In the experimental tasks, I examined the dependence of those deviations on auditory and kinaesthetic feedback as well as pianists' ability to predict and ultimately avoid those deviations. The underlying theoretical question was whether the unintended timing variations, like the intended ones, are part of the musical imagination, or whether they arise more directly from real-time perceptual or motoric activity. A more detailed discussion of the various tasks follows.

In the first task, the participants were simply required to play a short musical excerpt, the opening of a well-known *étude* by Chopin. That excerpt contains 36 nominally (i.e., notationally) equal IOIs but is known to elicit large expres-

sive deviations from isochrony. The accuracy with which the expressive pattern of IOI durations or *timing profile* could be reproduced from trial to trial was of interest. The data were also expected to replicate the earlier finding (Repp, 1997b) that the variability of individual IOIs increases with their intended (average) duration even when the within-performance variation in IOI durations is purely expressive in origin (i.e., not prescribed in the score). It should be noted that the expressive timing profile, being part of the performer's art, is different for each individual. Therefore, more attention was paid to individual differences in this study than is customary in psychology research.

In the second task, the pianists were required to play the same music without auditory feedback. The question was how accurately they would reproduce their individual expressive timing profile when they could rely only on auditory imagery and kinaesthetic feedback from the piano keyboard. Several earlier studies have examined the effect of eliminating auditory feedback in music performance but have found no significant deterioration (Banton, 1995; Finney, 1997; Gates & Bradshaw, 1974). However, Gates and Bradshaw looked only for changes in basic tempo, whereas Banton counted only errors in sightreading. Only Finney examined several performance parameters, including IOI variability. In none of those studies, however, was the focus specifically on expressive timing. The present task thus was expected to provide an especially sensitive test of the role of auditory feedback in timing control.

The next four tasks did not involve piano performance but required the participants to tap with a single finger on a response key. In one task (the fourth in sequence), they tapped in synchrony with an imagined expressive performance of the music. That task was like the playing condition without auditory feedback, except that kinaesthetic feedback from the piano keyboard was eliminated as well. Thus, expressive timing had to be generated entirely from an internal representation of the music. This novel task enabled me to assess the extent to which it could be done at all and also to examine the variability of the tapping performances relative to the piano performances.

In the other three tapping tasks, participants were required to tap in synchrony with an auditory pacing stimulus (the *model*). In one task (the third in sequence), the model was one of the pianist's own expressive performances, recorded a few minutes earlier. Although that stimulus was highly modulated in terms of its timing, I expected that the pianist would have no difficulty synchronizing with it accurately if he or she had a mental representation of the intended timing profile. Ideally, the model should have had the average timing of a pianist's 10 expressive performances so that the small but unsystematic timing variability, caused by imperfections of motor control, that is present in any individual performance would be reduced. Preparing such an average timing performance would have required extensive processing of the recorded musical instrument digital interface (MIDI) data, however, which was not fea-

sible within a single experimental session. Instead, in the fifth task, I presented as a model a computer-generated performance whose timing profile represented the average of 27 expressive performances by 9 advanced student pianists (see Repp, 1997a). That student average performance represented a typical timing profile for the music and sounded very smooth and natural. Therefore, I expected that the pianists would be able to synchronize with it about as well as with their personal timing profile. To what extent the accuracy of that synchronization depended on actually hearing the music was investigated in a sixth task in which the model was a sequence of clicks whose timing mimicked that of the note onsets in the student average performance. Clearly, accurate synchronization with such an irregularly timed click train would be very difficult if no musical context were available. The pianists were asked to imagine the music in time with the click train, however, and I expected that the mental representation would enable them to anticipate the timing variations and to achieve synchrony with the clicks almost as accurately as with the music. Thus, this was another test of their ability to generate an expressive timing profile from a real-time auditory image of the music.

In the seventh task, the participants were asked to play the music metronomically, without any expressive timing. There are precedents for that type of task in the music performance literature. Long ago, Seashore (1938) observed that a pianist attempting to play a Chopin nocturne metronomically "did not succeed very well" and tended "to be influenced by motives for interpretation" (p. 248). The correspondence between the pianist's metronomic and expressive timing profiles (in terms of durations of whole measures, shown in Seashore's Figure 11 on p. 247) was not very striking, however. Palmer (1989) asked 6 pianists to play the same excerpt "musically" and "unmusically". The correlations between the timing profiles of the two types of performance ranged from .42 to .87 (Palmer, personal communication, July 14, 1997). However, unmusical playing does not necessarily imply an intention to play metronomically, nor does it imply a change in timing alone. Some pianists may have focused on other performance parameters (dynamics, articulation) while leaving timing more or less the same; others may have deliberately distorted their timing. In a recent study, however, Penel and Drake (1998) found a very high correlation (.89) between the average timing profiles of expressive and "mechanical" performances of Schumann's "Träumerei" by 8 pianists. (The individual correlations were not reported.) In the present study, I further examined the extent to which traces of expressive timing survive an explicit intention to play strictly in time.

In the 8th task, the pianists again tried to play metronomically, but without auditory feedback. If systematic deviations from mechanical regularity were found in the preceding task, then I expected that this novel task would reveal whether the unintentional timing variation depended on hearing the music. In another task (the 10th in sequence),

the pianists tapped in time with an imagined metronomic performance. Here the question was whether any unintentional timing variations resembling the original expressive timing profile would still show up in tapping. If they did, that finding would suggest that they depended neither on auditory nor on kinaesthetic feedback, but rather were generated from a mental representation of the music.

The final 3 tasks involved synchronization with metronomic models. In one task (the 9th in sequence), the participants tapped along with one of their own metronomic performances, recorded a few minutes earlier. To the extent that that performance contained systematic deviations from mechanical evenness, the question of interest was whether those (effectively subliminal) deviations would be anticipated in tapping. In the 11th task, the participants were presented with a computer-generated musical model that was in fact metronomically timed. One might expect that, in that condition, the participants would tap metronomically. However, in an earlier study in which the same music was used, Repp (in press) showed this was not the case. Rather, there were systematic variations in the asynchronies between taps and note onsets and, hence, also in the intertap intervals (or tap IOIs). Those variations were related to the typical expressive timing profile for the music. That is, participants produced slightly longer tap IOIs where expressive lengthening seemed appropriate in the music and exhibited compensatory shortening of IOIs elsewhere. In the present task, that intriguing finding was expected to be replicated. It would suggest that on-line processing or active recall of a musical structure can affect the mental timekeeping functions that govern perceptual-motor synchronization. Finally, the pianists were asked to tap to a metronomic sequence of clicks—the ultimate baseline condition. They were asked to imagine the music while listening to the clicks, however, and therefore I considered it possible that there would be some systematic, music-related variation in the tap IOIs even in that simple condition.

In summary, then, in the present study I attempted to

determine to what extent the pattern and variability of systematic timing variation depend on (a) the intention to play expressively, (b) the presence of auditory feedback, and (c) the presence of kinaesthetic feedback from a piano keyboard. Furthermore, I investigated to what extent pianists' ability to predict and synchronize with expressive timing variation in stimuli depends on (a) the presence and degree of such variation, (b) its similarity to the pianists' own timing profile, and (c) hearing the music. The results were expected to provide new information about the mental representation of expressive timing and about its voluntary and involuntary manifestations in motor behavior. For easy reference, the 12 tasks are summarized in Table 1.

Method

Participants

Six pianists with advanced technical and musical skills participated in the study. One was the author (B.R.), an amateur aged 52 at the time. He was much older but less skilled than the other participants, who were all in their 20s or late teens and represented very high levels of technical accomplishment. Three of the young pianists (D.G., T.C., H.S.) were men; 2 (K.S., M.S.), women. D.G. had recently earned a master's degree in piano performance from the Yale School of Music; T.C. and H.S. were graduate students in the same program; K.S. was a senior in Yale College who entered the piano graduate program the following year; and M.S. was one of the most gifted pianists in Yale College, a sophomore at the time. The 5 young pianists were paid for their participation.

The Music

The musical excerpt used throughout was the opening of Chopin's Etude in E major, Opus 10, No. 3, with a final chord added to give closure to the excerpt. A computer-generated score without slurs and expression marks is shown in Figure 1a. That excerpt has been used in a number of previous studies by the author (Repp, 1997a, 1998a, 1998c,

TABLE 1
Summary of Experimental Tasks 1–12

	Expressive	Metronomic	Pacing
<i>Piano playing</i>			
With sound	1	7	Internal
Without sound	2	8	Internal
<i>Finger tapping</i>			
With own performance	3	9	External
With imagined performance	4	10	Internal
With computer performance	5	11	External
With click sequence	6	12	External

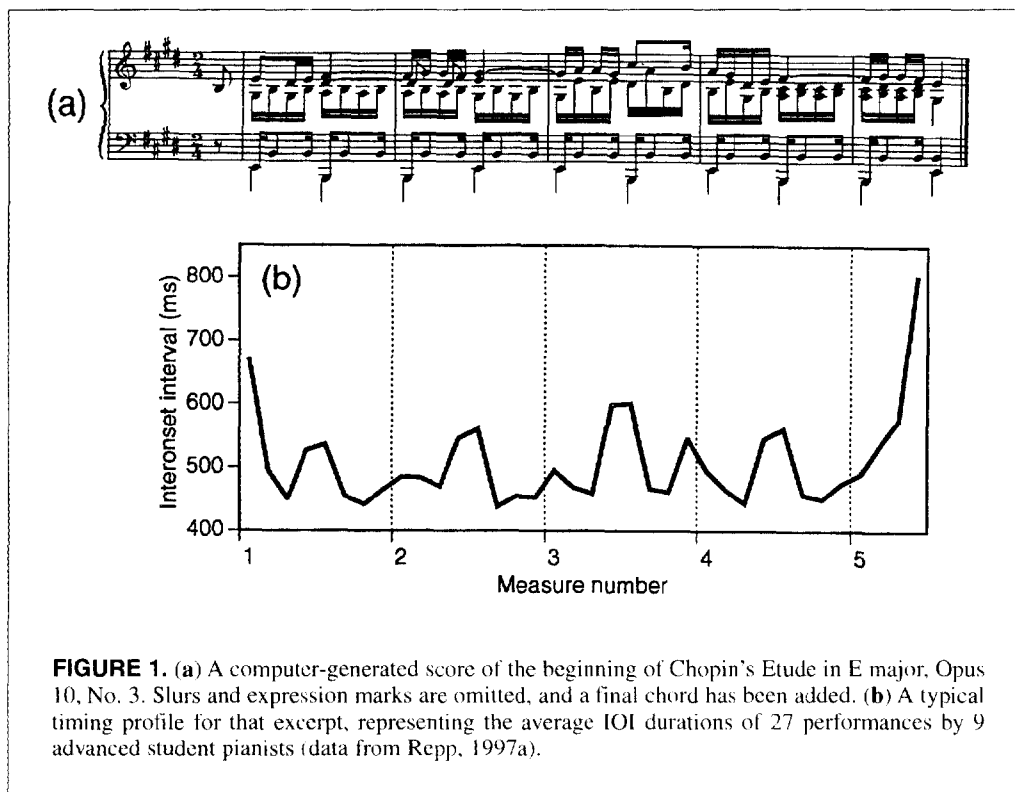


FIGURE 1. (a) A computer-generated score of the beginning of Chopin's Etude in E major, Opus 10, No. 3. Slurs and expression marks are omitted, and a final chord has been added. (b) A typical timing profile for that excerpt, representing the average IOI durations of 27 performances by 9 advanced student pianists (data from Repp, 1997a).

1998e, in press) and is known to invite large tempo modulations in the service of expression.

Following an initial 8th-note upbeat, note onsets in one or more voices occur at regular nominal IOIs corresponding to quarter beats (16th notes) in the score. The actual durations of those IOIs constitute the timing pattern or timing profile of a performance. The nominally longer IOI associated with the initial upbeat was disregarded in all the subsequent analyses, so a timing profile consisted of 36 nominally equal IOIs. The vertical division of the music into four or five voices (soprano melody, mezzo and alto accompaniment, and tenor and bass rhythmic foundation) is irrelevant to the definition of IOIs. However, the horizontal segmentation of the soprano melody into groups or gestures ending in longer notes during which the accompaniment continues, together with the harmonic changes coinciding with those long notes, is the major structural factor influencing expressive tempo modulation. This can be seen in Figure 1b, which shows a typical timing profile obtained by averaging the timing profiles of 27 performances by 9 young pianists (see Repp, 1997a, 1998e). In addition to a great lengthening of the initial downbeat IOI and of the IOI preceding the final chord, the two IOIs surrounding the onset of a group-final melody note are typically lengthened, as well as the initial IOI of the fourth melodic gesture (the final IOI in bar 3), which starts earlier than the other gestures and has a harmonic change at the beginning. A small tendency to slow down before the beginning of a melodic gesture (the first IOIs in bars 2, 3, and 5) can also be seen. As Repp (1997a)

has shown, young pianists and amateurs usually do not stray far from that typical pattern, even though they each show an individual variant of it. Radically different timing patterns are generally found only among experienced concert artists, often those of earlier generations (Repp, 1997a, 1998c).

Design and Equipment

As described above, the experiment included 12 tasks (see Table 1), each of which was carried out 10 times. Four tasks (1, 2, 7, and 8) involved playing on a piano keyboard; the other 8 involved rhythmic tapping with the finger on a single response key, 6 of them in synchrony with an auditory model. Tasks 1–6 concerned expressive timing; Tasks 7–12, metronomic timing. The sequence of the tasks was the same for all participants. The experimental session lasted about 90 min, with a break after the first half.

The pianists played on a Roland RD-250s digital piano featuring a weighted keyboard, a simple on-off sustain pedal switch, and fairly realistic sound ("Piano I") that could be heard over Sennheiser HD540 II earphones. The keyboard and pedal actions were recorded in MIDI format by a simple program written in MAX, running on a Macintosh Quadra 660AV computer. In the tapping tasks, participants tapped on the *enter* key located in the lower right corner of the Macintosh extended keyboard, except for D.G. who was left-handed and tapped on the \sim key in the upper left corner of the keyboard. Programs written in MAX played the auditory models on the digital piano and registered the onsets and offsets of the key depressions.¹

I determined interonset intervals in the recorded music performances by first identifying the note with the highest pitch in each metrical position and then calculating the differences between the onset times of those primary notes; they included all melody notes and the highest accompaniment notes during sustained melody notes. The IOIs were thus derived from the right-hand part of the music only, which arguably was the pianists' focus of attention.

Procedure

Task 1: Expressive performance. To begin with, the pianist was asked to warm up briefly on the digital piano and to then play the Chopin excerpt 10 times from the computer-generated score (Figure 1a) that was placed on a music stand. The pianist was asked to play with fine expression and not to change the interpretation across repetitions. Although all participants knew the Chopin Etude, only 2 (B.R., D.G.) had actually studied it previously. However, it presented no sightreading problems for anyone.² After the 10 performances had been recorded, the pianist was asked to play the excerpt one more time. That 11th performance served as the model in Task 3.

Task 2: Expressive performance without auditory feedback. The earphones were unplugged from the digital piano and removed from the pianist's head. Then the pianist was asked to play the excerpt 10 times, exactly as before.

Task 3: Tapping in synchrony with one's own expressive performance. The pianist was seated in front of the computer and tapped with the index finger on the computer keyboard while listening to the output of the digital piano over the earphones. He or she heard the 11th performance recorded in Task 1 and was asked to tap in synchrony with it, beginning on the first downbeat and tapping with every 16th note (i.e., 37 times). Three practice trials were presented before the 10 test trials, which were separated by a few seconds of silence.

Task 4: Tapping in synchrony with an imagined expressive performance. The earphones were unplugged from the digital piano and removed from the pianist's head. Then, the pianist was asked to tap 10 times in synchrony with his or her own imagined expressive performance, leaving a few seconds between repetitions. In this task, the initial upbeat was tapped out as well, except by B.R. (who thought of this instruction only after running himself first in the experiment) and by H.S. (who did not follow the instruction). Pianists who wished to look at the score while tapping were allowed to do so.

Task 5: Tapping in synchrony with a typically timed computer performance. This task was like Task 3, but the auditory model was a computer-generated performance with the typical timing profile shown in Figure 1b. All nominally simultaneous note onsets were very nearly synchronous in this model.

Task 6: Tapping in synchrony with a series of clicks timed according to the typical timing profile. This was like Tasks 3 and 5, but the auditory model was a series of clicks whose

IOIs mimicked the typical timing profile (Figure 1b). The pianist was asked to imagine the music while tapping in synchrony with the "clicks". The clicks were really the high-pitched note C8 (4,168 Hz), produced on the digital piano. Its sound prominently included the contact noise of a wooden piano key with the key bed, and it decayed fairly rapidly following the nominal offset.

Task 7: Metronomic performance. This task was like Task 1, except that the pianist was asked to play metronomically, without expressive timing, leaving everything else (including pedaling) as much the same as possible.

Task 8: Metronomic performance without auditory feedback. This task was like Task 2, but with metronomic timing.

Task 9: Tapping in synchrony with one's own metronomic performance. This task was like Task 3, but an 11th inexpressive performance, recorded at the end of Task 7, served as the model. No practice trials were given.

Task 10: Tapping in synchrony with an imagined metronomic performance. This task was like Task 4, but with an imagined metronomic performance.

Task 11: Tapping in synchrony with a metronomically timed computer performance. This task was similar to Task 5, except that the computer-generated model had fixed nominal IOIs of 500 ms (1,000 ms for the initial upbeat). No practice trials were given.

Task 12: Tapping in synchrony with a series of metronomically timed clicks. This task was like Task 6, except that the clicks had fixed nominal IOIs of 500 ms (1,000 ms for the first IOI). The pianist was encouraged to imagine the music while tapping, which, in any case, could hardly be avoided after hearing the excerpt so many times. There were no practice trials.

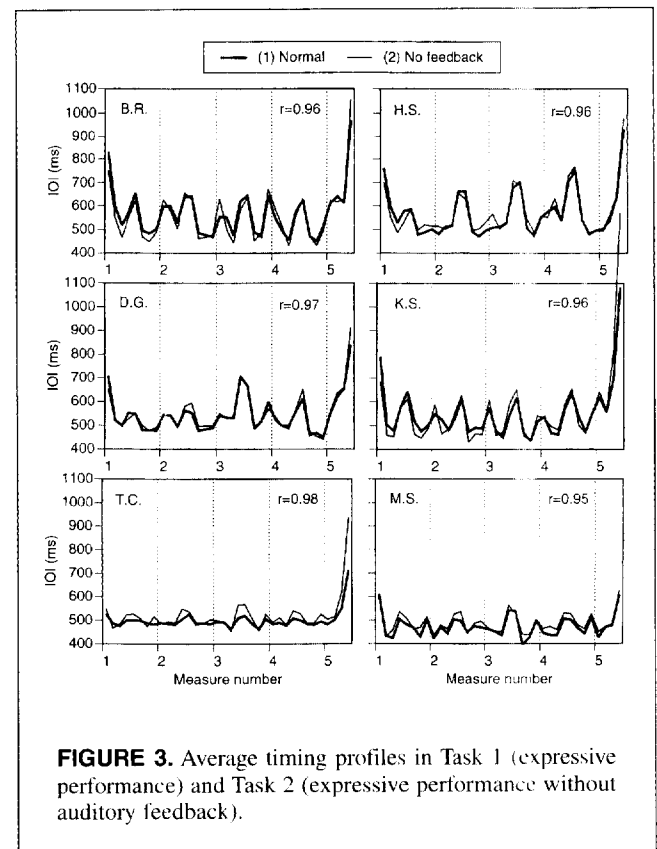
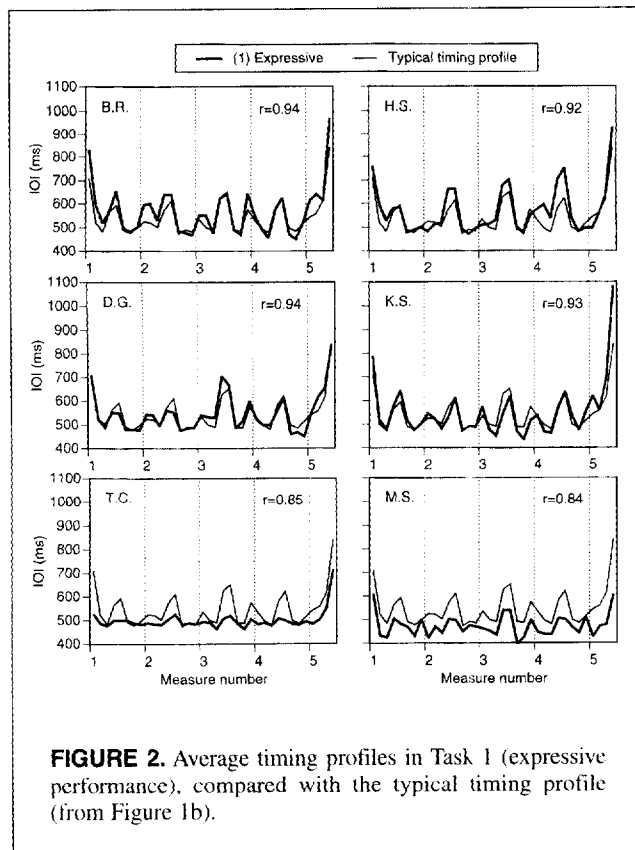
Results and Discussion

This section is divided into two parts, the first dealing with internally paced timing (piano playing and tapping to imagined music) and the second dealing with externally paced timing (the synchronization tasks).

Internally Paced Timing (Tasks 1, 2, 4, 7, 8, and 10)

Expressive Playing With and Without Auditory Feedback (Tasks 1 and 2)

The average timing profile of Task 1 for each of the 6 pianists is compared with the typical (student-average) timing profile (Figure 1b) in Figure 2. The correlations were high in all cases, as expected. However, T.C. unexpectedly produced only a minimally modulated expressive timing profile, except for a final ritard. When later asked, he affirmed that he preferred to play the E-major Etude "straight." (He generally tended to favor 20th century music over Romantic music.) M.S.'s profile was also relatively weakly modulated, whereas H.S. showed stronger modulations than is typical. All individual Task 1 profiles showed considerable similarity to each other, with correlations ranging from .68 to .91.



The average timing profiles of Tasks 1 and 2 for each of the 6 pianists are compared in Figure 3. It is clear that the absence of auditory feedback had no dramatic effects on either profile shape or basic tempo. Each pianist was able to reproduce his or her characteristic timing profile when the sound was only imagined. Correlations between Task 1 and Task 2 profiles are shown in the figure and ranged from .95 to .98. The only major differences were in the extent of the final ritard: Both T.C. and K.S. produced a much longer final IOI in the absence of feedback, and 3 of the other pianists showed a small tendency in the same direction. Even small differences tended to be significant because within-task standard errors were often below 10 ms. (Measures of variability are discussed later.) That finding was confirmed in separate two-way analyses of variance (ANOVAs) on each pianist's data, with repetitions as the random variable, task as a between-repetitions factor, and positions (36) as a within-repetitions factor. Besides huge position main effects, each analysis yielded a highly significant Task \times Position interaction. (The term *highly significant* implies $p < .001$ throughout this article, and only lower significance levels are mentioned, if necessary.) In addition, 2 pianists (T.C. and M.S.) showed a highly significant task main effect, which suggests a change in basic tempo, although Figure 3 indicates that for T.C. that effect was caused mainly by greater expressive lengthening in Task 2 than in Task 1. Despite these significant differences, however, these data are consistent with earlier suggestions in the

literature (Finney, 1997) that auditory feedback is not essential for good timing in piano performance.³

Imagined Expressive Timing: Playing Versus Tapping (Tasks 2 and 4).

The average timing profiles of Task 2 (playing without auditory feedback) and Task 4 (tapping in synchrony with an imagined performance) are compared in Figure 4. That comparison assesses the pianists' ability to imagine (or *audiate*; cf. Gordon, 1993) and produce their expressive timing profile away from the instrument. Here, some larger differences can be seen. Nevertheless, 4 pianists—those with highly modulated timing profiles (B.R., D.G., H.S., and K.S.)—clearly were able to reproduce their timing pattern quite well by tapping; their correlations ranged from .87 to .96. T.C. and M.S., however, produced very nearly flat tap-timing profiles, except for a final ritard in T.C.'s case. Because of that final ritard, T.C.'s correlation of .94 is misleading; if the final two IOIs are omitted, the correlation drops to a nonsignificant .32. M.S. did not even show a final ritard in tapping, though she had a slightly lengthened first IOI. Her correlation was .45 ($p < .01$) without the initial IOI. The fact that the correlation was still significant suggests that some traces of her expressive timing survived, but they were clearly minimal compared with the tap-timing profiles of B.R., D.G., H.S., and K.S. It seems unlikely that T.C. and M.S. misunderstood the instructions, especially because they had not yet been

asked to play metronomically. Rather, their mental representation of the music did not seem to contain significant expressive timing variations—in other words, they really intended to play the music metronomically (see the discussion of Tasks 7 and 10).

Among the other 4 participants, D.G. was most successful in tapping out his expressive timing pattern. K.S., too, reproduced her profile shape well but raised the valleys in her profile; that is, she performed with a slower basic tempo with smaller modulations. (In this excerpt, there may be good reasons for identifying the basic tempo with the valleys in the profile; see Repp, 1998a, and the later discussion.) K.S. also reduced her final ritard substantially, as did all others except D.G. H.S., like K.S., basically reduced his tempo modulations, in this case without changing his basic tempo; however, there were also some changes in small details. B.R.'s tap-timing profile showed shifts of several peaks to the right as well as a substantial reduction of the peak at the end of bar 3. Each pianist's differences seemed idiosyncratic.

ANOVAs on the individual data showed highly significant Task \times Position interactions for all pianists and highly significant task main effects (i.e., changes in average tempo) for all but B.R., whose task effect was only marginally significant. Position main effects were huge, of course. I conducted separate one-way ANOVAs on the Task 4 data of T.C. and M.S. to determine whether there was still significant timing variation in their tapping. The position main

effects were highly significant, both for T.C. with the final IOI omitted, $F(34, 306) = 8.57, p < .001$, and for M.S., $F(35, 315) = 2.87, p < .001$, which indicates some reliable residual timing variation in the tapping task, though its magnitude seemed fairly negligible.

In summary, the data of 4 pianists suggest that intentional expressive timing has a fairly accurate mental representation that can be accessed and acted out away from the piano keyboard. Two pianists, however, did not seem to have such a representation, at least for the present musical excerpt. Their playing intentions seemed to be closer to those of metronomic performances, to which I turn next.

Expressive Versus Metronomic Playing (Tasks 1 and 7)

In Figure 5, the expressive timing profiles of Task 1 are compared with the intended-to-be-metronomic timing profiles of Task 7. As predicted, the metronomic profiles were not completely flat but retained some modulation that was qualitatively similar to that in the expressive profiles. The correlations between the Task 1 and Task 7 profiles ranged from .75 to .92. Moreover, all 6 pianists' metronomic profiles were similar to each other, with correlations ranging from .60 to .91. That is effectively the same range as that of the intercorrelations among the expressive timing profiles, even though the range of IOI durations (and, hence, the magnitude of systematic relative to random timing variation) was much smaller. Apart from the final ritard, T.C. played with similarly small modulations in Tasks 1 and 7.

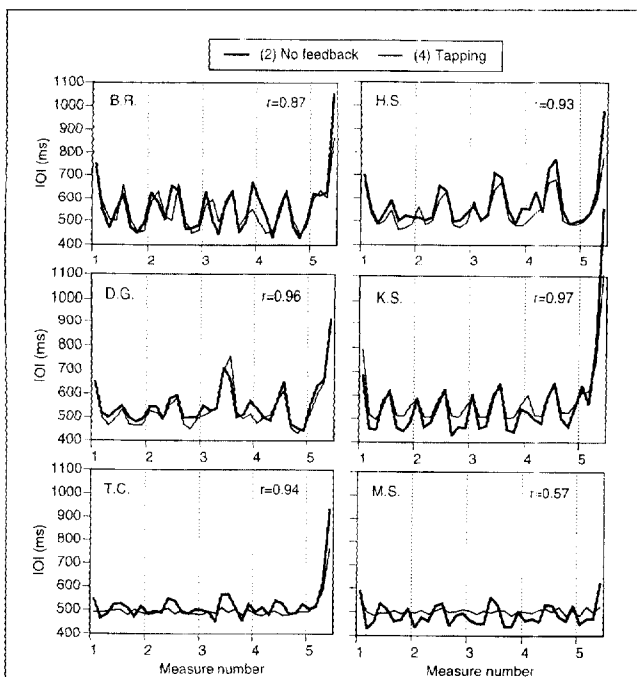


FIGURE 4. Average timing profiles in Task 2 (expressive performance without auditory feedback) and Task 4 (tapping to an imagined expressive performance).

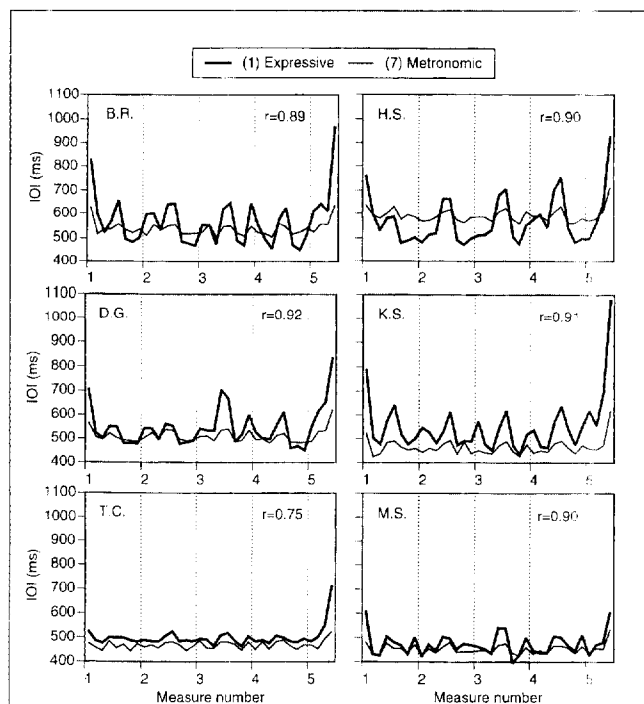


FIGURE 5. Average timing profiles in Task 1 (expressive performance) and Task 7 (metronomic performance).

M.S., however, did show some reduction of her Task 1 timing modulations in Task 7. Still, her modulations in Task 1 may not have been intentional, or else they should have been consciously accessible in Task 4 (tapping to an imagined performance).

The tempo adopted spontaneously by 4 of the pianists (D.G., K.S., T.C., M.S.) in metronomic playing provides support for the assumption (Repp, 1998a) that the basic tempo of an expressive performance of the Chopin excerpt corresponds to its maximal tempo (i.e., the valleys of the timing profile). However, H.S. clearly played more slowly in Task 7 than in Task 1, and B.R. slightly so. In ANOVAs on the individual data, the task main effect was highly significant for all pianists except H.S., which indicates that his metronomic performances had the same average IOI duration as his expressive performances. Naturally, the Task \times Position interaction was highly significant for all pianists, although T.C.'s F value was small when the final IOI was omitted, $F(34, 612) = 3.64, p < .001$. The significance of the timing variations in the metronomic condition are assessed later.

The results of this comparison confirm earlier findings (Drake & Palmer, 1993; Palmer, 1989; Penel & Drake, 1998) of a close correspondence between expressive timing and the residual timing variations in intended metronomic or mechanical playing. Presumably the residual variations are unintended and inaccessible to conscious control. In the following comparison, I examine whether they depend on auditory feedback.

Metronomic Playing With and Without Auditory Feedback (Tasks 7 and 8)

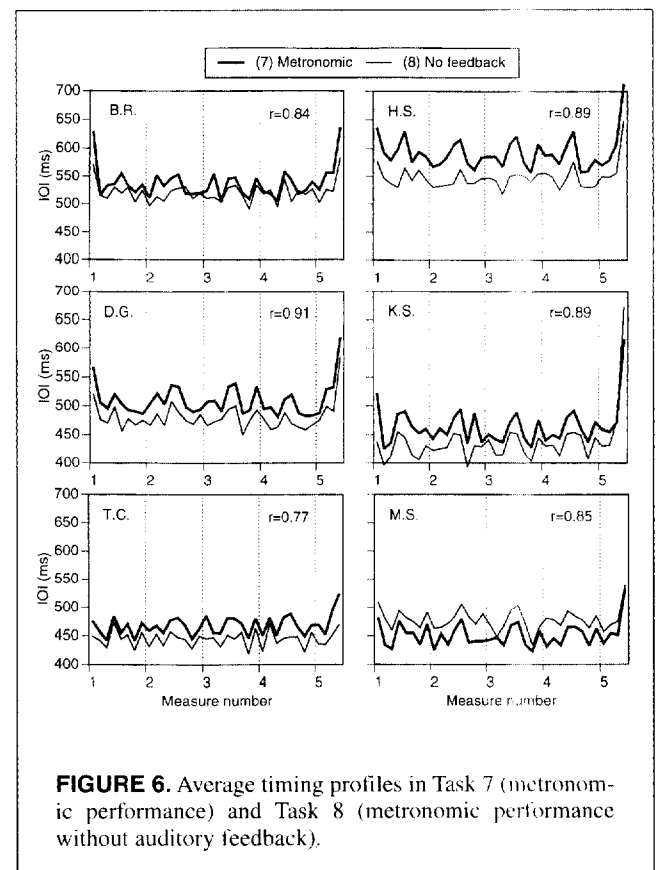
The metronomic timing profiles of Task 7 are shown magnified in Figure 6, where they are compared with the metronomic timing profiles in the absence of auditory feedback (Task 8). It is clear that there was a high similarity between those profiles, just as there had been between the corresponding expressive profiles (Figure 3). The correlations ranged from .77 to .91. Thus, the involuntary tempo modulations were clearly not dependent on auditory feedback. For 4 pianists, the no-feedback metronomic profiles (Task 8) also correlated highly with the no-feedback expressive profiles (Task 2), with values between .81 (H.S.) and .95 (K.S.), but B.R. and T.C. showed lower correlations (.66 and .49, $p < .01$, respectively). The last two correlations were distinctly lower than those between the corresponding with-feedback profiles (Tasks 1 and 7) for these 2 pianists.

The absence of feedback seemed to have an effect on the basic tempo of the metronomic performances, however, which had not been evident in expressive performance (Figure 3). Five pianists increased their tempo in Task 8, whereas M.S. slowed down. Only K.S. lengthened the final IOI, as she had done in her expressive performances in Task 2; the others showed no trace of that earlier tendency. The individual ANOVAs showed all main effects and interactions to be highly significant. Thus, both the changes in

basic tempo and in the timing patterns were highly reliable. The F values for the Task \times Position interactions were relatively small, however, ranging from 2.57 (T.C.) to 8.41 (B.R.). Although they provided evidence of some reliable effects of auditory feedback on involuntary timing variation, there seemed to be little systematicity or theoretical significance in those differences.

Imagined Metronomic Timing: Playing Versus Tapping (Tasks 8 and 10)

In Figure 7, the involuntary tempo modulations of metronomic performances without feedback (Task 8) are compared with those observed in tapping along with an imagined metronomic performance (Task 10). Recall that T.C. and M.S. produced nearly flat timing profiles when asked to tap out their imagined expressive performances (Task 4). Now, however, all 6 pianists produced fairly flat profiles, although some (D.G., K.S.) still showed lengthening of initial and final IOIs. The correlations between the Task 8 and Task 10 profiles were clearly lower than previous correlations, ranging from .07 to .79. (A correlation of .41 is significant at $p < .01$.) Because some of the higher correlations were evidently caused by the initial and final IOIs, the correlations were recomputed without those IOIs: they then ranged from .00 (B.R.) to .46 (K.S.). That last correlation was still significant, as was that of D.G. (.45). Thus, there were still traces of involuntary tempo modulations even in



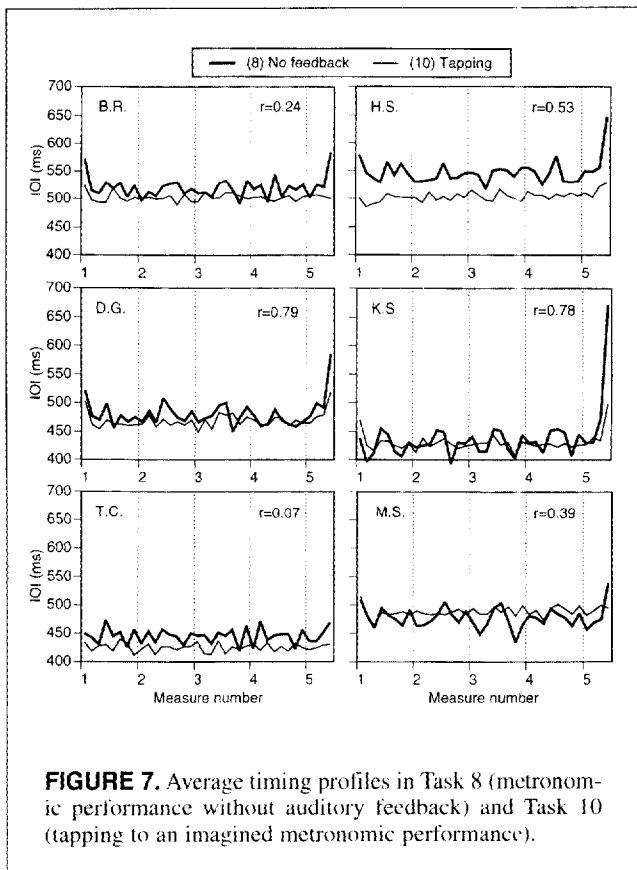


FIGURE 7. Average timing profiles in Task 8 (metronomic performance without auditory feedback) and Task 10 (tapping to an imagined metronomic performance).

the tapping condition, but only for a few pianists, perhaps those with the strongest musical imagination. Whereas the intercorrelations among the individual Task 7 profiles had ranged from .60 to .91, those among Task 10 profiles ranged from -.16 to .57, with one exceptional value of .83 (between D.G. and K.S.), which dropped to .47 when the initial and final IOIs were omitted. Only 4 of the 15 intercorrelations were significant ($p < .01$). Thus, any remaining systematic

variation in Task 10 was rather marginal. A similar conclusion may be drawn from the correlations between the Task 4 and Task 10 profiles, which originally ranged from .16 to .85 but dropped to range from .11 to .55 (D.G.) after the initial and final IOIs were omitted. Two of the six correlations remained significant.

The individual ANOVAs showed all main effects and interactions to be highly significant, except for the task main effect for D.G., which was only marginally significant ($p < .03$). Thus there was evidence for changes in basic tempo (slower tapping than playing for 5 pianists, with M.S., once again, being the exception) and for changes in profile shape. To determine whether the residual variation in the tapping condition was statistically reliable, I conducted separate one-way ANOVAs on the Task 10 data. The position effect remained highly significant for all pianists except M.S. ($p < .04$) and T.C. ($p < .003$). It was still highly significant for H.S. and K.S. when their initial and final IOIs were omitted, although the F values were small. Thus, there was still reliable timing variation even in the tapping condition, but it seemed negligible because of its small magnitude.

Variability Across Repetitions

Data on the variability of individual IOIs across the 10 repetitions in the expressive Tasks 1, 2, and 4 are summarized in Table 2. The relationship of main interest was the predicted increase in the standard deviation with IOI duration (Repp, 1997b). The correlations between those two variables are presented in the columns labeled (a); the correlations were positive and significant for 5 of the 6 pianists. Only M.S. showed nonsignificant correlations in all three tasks, and T.C.'s correlations must be taken with a grain of salt because they rested almost entirely on his long final IOI. However, the correlations of the other 4 pianists—those who had sufficiently modulated expressive timing profiles—provide support for the hypothesis that IOI variability increases with IOI duration in each of the three tasks.

TABLE 2
Variability in Tasks 1, 2, and 4

Pianist	Task 1				Task 2				Task 4			
	(a)	(b)	(c)	(d)	(a)	(b)	(c)	(d)	(a)	(b)	(c)	(d)
B.R.	.67***	20	8.6	1.4	.68***	28	7.5	1.9	.76***	34	15.0	1.6
D.G.	.55***	22	8.5	2.0	.56***	23	10.4	1.3	.54***	30	6.4	1.8
T.C.	.70***	16	11.3	0.5	.93***	18	31.8	2.0	.87***	21	16.5	1.4
H.S.	.44**	24	4.5	1.9	.68***	26	9.8	2.8	.73***	33	18.9	1.6
K.S.	.92***	24	12.9	2.4	.83***	27	7.9	1.7	.78***	23	9.8	1.6
M.S.	.25	21	5.4	1.3	.16	21	3.9	0.6	.11	26	4.1	1.8

Note. (a) Correlation between average interonset interval (IOI) duration and standard deviation; (b) estimated standard deviation (ms) at IOI = 500 ms; (c) slope of regression line ($\times 100$); (d) basic tempo variability: coefficient of variation (%) of mean IOI.
** $p < .01$, *** $p < .001$.

Measures related to the intercept and slope of the linear regression between the two variables are reported in the columns labeled (b) and (c), respectively. Instead of the meaningless intercept at IOI = 0, the estimated value for IOI = 500 ms is given; that value is the standard deviation in the vicinity of (or slightly below) the average IOI duration. Those standard deviations, which ranged from 16 to 24 ms in Task 1, from 18 to 28 ms in Task 2, and from 21 to 34 ms in Task 4, reflected an increase in variability across the three tasks that was significant in a one-way ANOVA, $F(2, 10) = 8.02$, $p < .01$. However, the slopes (multiplied here by 100 so that they represent the increase in standard deviation per 100 ms of IOI) varied considerably and did not show systematic differences among the tasks. They may be compared with the values under (d), which represent the coefficients of variation of the mean IOI (i.e., averaged across all positions in the music). In other words, the values in columns (d) represent the variability of the average tempo (closely related to, if not identical with, the basic tempo) across trials, and, because tempo variability affects IOIs and their standard deviations in a multiplicative fashion, (d) represents the increase in variability per 100 ms of IOI duration expected on the basis of variability in basic tempo alone. It can be seen that (d) was substantially smaller than (c) in all cases. Tempo variability was generally below 3%, often below 2%, whereas IOI variability increased with IOI duration at a rate of anywhere between 4 and 19 ms per 100 ms of IOI.

The variabilities in the metronomic Tasks 7, 8, and 10 are not discussed in this article because the small range of IOI durations gave little room for systematic relationships between IOI duration and variability.

Lag-1 Autocorrelations

In tasks requiring free tapping at a fixed rate, the Lag-1 autocorrelation of the tap IOIs provides an index of automatic error correction or simply motor variability: When a constant average rate must be maintained, relatively long IOIs tend to be followed by a relatively short ones and vice versa, resulting in a negative Lag-1 autocorrelation (Wing

& Kristofferson, 1973). The present metronomic tasks (Tasks 7, 8, and 10) approximated that situation, but they did contain residual systematic timing deviations. In the expressive timing tasks (Tasks 1, 2, and 4), of course, the rate of events was far from constant. However, there may have been a fixed timing schedule or plan around which the actual IOIs oscillated as a result of motor variability, and the best estimate of that plan is the average timing profile. Therefore, Lag-1 autocorrelations were computed on the deviations from the average timing profile in each trial. The average correlations are shown in Table 3.

In the metronomic tasks, the correlations were mostly negative, as expected, but often rather small and nonsignificant. In the expressive tasks, T.C. and M.S., the pianists with the least modulated timing, also tended to show negative correlations, whereas the 4 pianists who had strongly modulated expressive timing profiles tended toward positive Lag-1 autocorrelations. That finding indicates that the assumption of an invariant timing plan may not be justified. The intended timing profile probably varied from trial to trial in scale (mean and within-trial standard deviation), if not also in shape, and these scale variations introduced positive covariation among adjacent IOIs (see also Repp, 1997b).

Externally Paced Timing (Tasks 3, 5, 6, 9, 11, and 12)

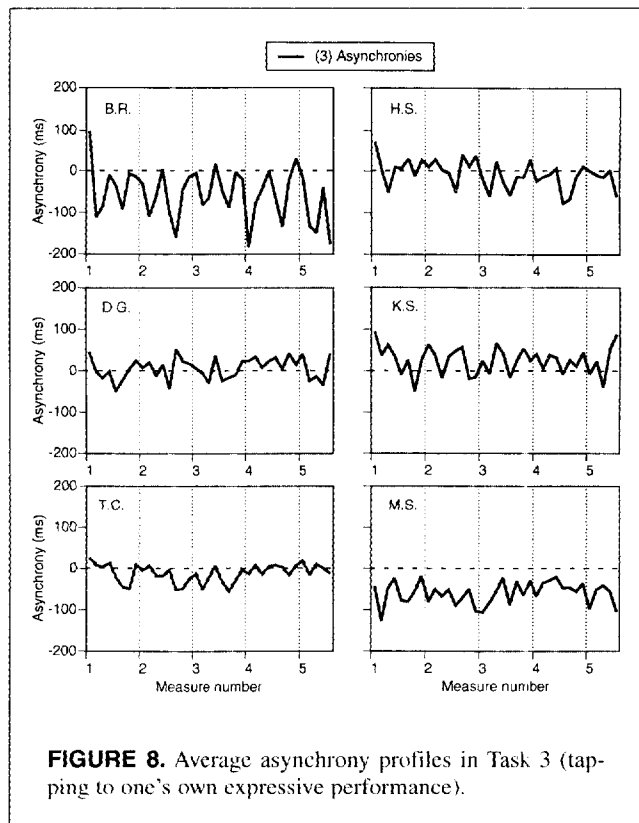
Tapping to One's Own Expressive Performance (Task 3)

The average asynchronies between taps and the model's primary-note onsets in Task 3 are shown in Figure 8. Two things are evident. First, the participants did not show a constant asynchrony, which indicates that they had some difficulty synchronizing precisely with their own performance. That observation is particularly obvious in the case of B.R. (the only true amateur in the group), who showed markedly poorer synchronization than the others. Second, the anticipation error usually found in synchronization tasks (see, e.g., Aschersleben & Prinz, 1995) was not shown by 2 pianists (D.G., K.S.) and was only weakly or intermittently shown by 2 others (T.C., H.S.). Only B.R. and M.S. showed a strong tendency to anticipate. One-way ANOVAs on the

TABLE 3
Average Lag-1 Autocorrelations of the Deviations From the Average Timing Profile in Six Internally Paced Timing Tasks

Pianist	Task 1	Task 2	Task 4	Task 7	Task 8	Task 10
B.R.	.25***	.11*	.28***	-.10	-.08*	-.09
D.G.	.23***	.19**	.04	-.08	-.08*	-.02
T.C.	-.01	.10	-.13*	-.13*	-.13	-.16
H.S.	.29***	.20***	.23***	.14*	.05	-.10
K.S.	.16***	.04	.07	-.11*	-.02	-.14*
M.S.	-.27***	-.11*	-.23**	-.27***	-.15**	-.15**

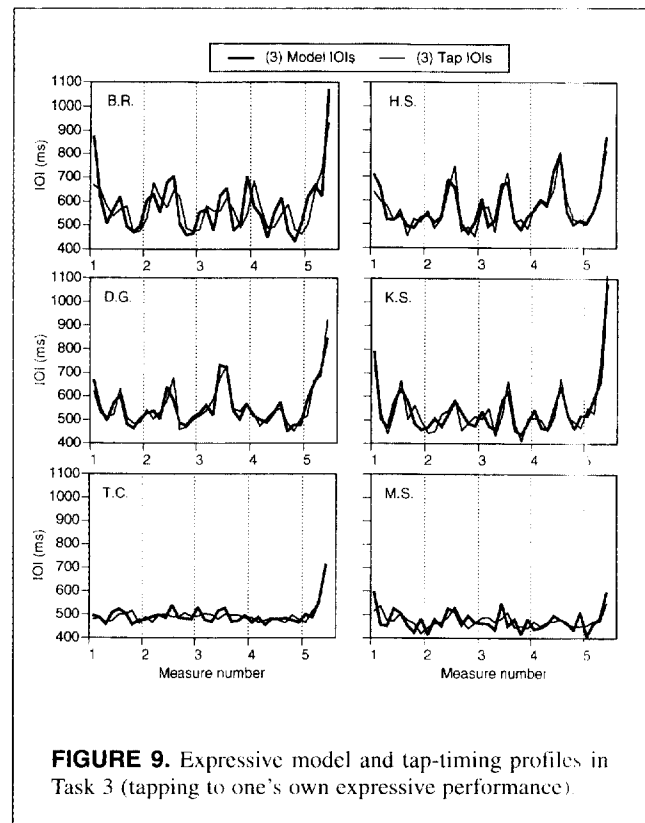
Note: Asterisks (*) indicate significance based on *t* tests across the 10 trials.
* $p < .05$, ** $p < .01$, *** $p < .001$.



data showed the position effect to be highly significant for all 6 pianists. It is interesting that T.C. and M.S., who were tracking much smaller timing modulations than the other pianists, showed asynchrony variation of about the same magnitude as H.S., D.G., and K.S.

The timing profiles of the expressive models and of the accompanying taps (averaged across the 10 repetitions) in Task 3 are shown in Figure 9. To remind the reader, each pianist's model was a single, 11th expressive performance from Task 1; therefore, its timing profile was similar to, but not identical with, the average Task 1 timing profile (Figure 2). It is clear that B.R. consistently underestimated the peaks (long IOIs) in the model and had to make up for that by lengthening the following tap IOI(s). Similar but much smaller tendencies can be seen in the other pianists' data, although they (at least H.S., D.G., and K.S.) were generally very successful in predicting their own expressive timing profiles. An expressive lengthening in the model was never overestimated; virtually all systematic synchronization errors derived from underestimations that were subsequently compensated for. That finding may well be related to the tendency to show smaller modulations in expressive tapping (Task 4) than in expressive playing (Task 2; see Figure 4): Physical interaction with the instrument may amplify expressive intentions somewhat.

The tendency to underestimate long IOIs implies a negative Lag-1 correlation between the asynchrony profiles (Figure 8) and the model timing profiles (Figure 9). The Lag 1 derives from the fact that the asynchrony is measured



at the end of an IOI; thus, for example, the large negative asynchrony in the first position of bar 4 in B.R.'s asynchrony profile (Figure 8) reflects his underestimation of the long IOI in the last position of bar 3 (Figure 9), which extends from the onset of the last note in bar 3 to the onset of the first note in bar 4. The Lag-1 correlations were highly significant for B.R. ($r = -.80$), H.S. ($r = -.65$), and M.S. ($r = -.77$); they fell short of significance for D.G. ($r = -.36$) and T.C. ($r = -.32$); and K.S. actually showed a small positive correlation ($r = .15$), mainly because of her accurate prediction of her extremely long final IOI.

Tapping to an Expressive Computer Performance and to a Similarly Timed Sequence of Clicks (Tasks 5 and 6)

In these tasks, T.C. and M.S., the 2 pianists who exhibited only slightly modulated expressive timing profiles in Task 1 and, hence, were not seriously challenged in Task 3, were forced to track a stimulus with a strongly modulated timing profile. All pianists were presented with the same expressive timing pattern (Figure 1b), carried either by music (Task 5) or by clicks (Task 6). In Figure 10, the asynchrony profiles for those two tasks and the correlations between them are shown. The correlations were moderately high and significant for all pianists, indicating similar responses in both tasks. The difference between B.R. and the other pianists was less striking here, especially in Task 6, where he was (surprisingly) more accurate than in Task 5. As in Task 3, D.G., H.S., and K.S. showed no consistent anticipation tendency.

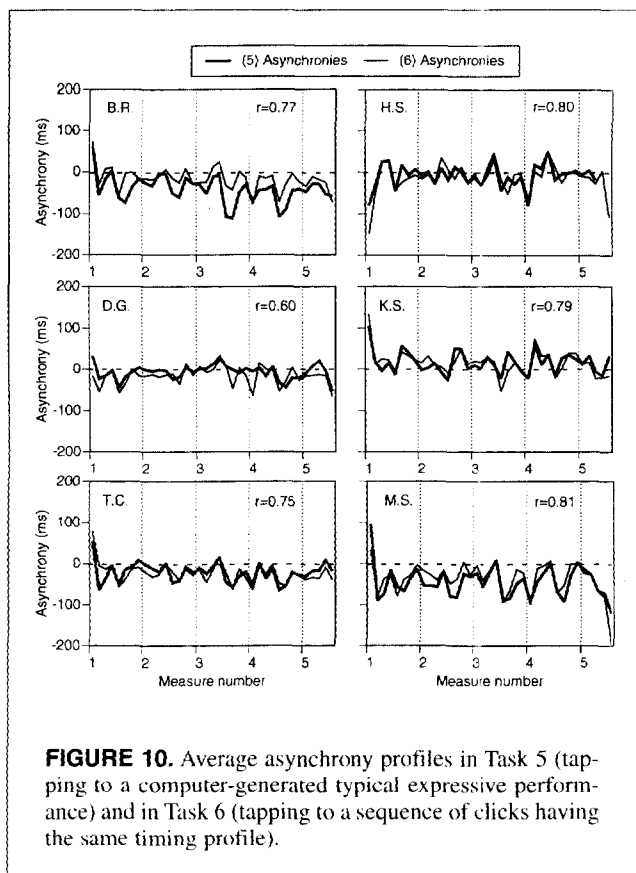


FIGURE 10. Average asynchrony profiles in Task 5 (tapping to a computer-generated typical expressive performance) and in Task 6 (tapping to a sequence of clicks having the same timing profile).

Two-way ANOVAs confirmed that all pianists showed highly significant systematic variation in asynchronies. However, the Task \times Position interaction was also highly significant for all 6 pianists (even though the F values were small), which indicates some differences in tracking music versus clicks.⁴ The task main effect, on the other hand, was highly significant only for B.R., significant ($p < .01$) for D.G., marginally significant for M.S. ($p < .05$), and non-significant for H.S., K.S., and T.C. Because the musical tones had slower amplitude rise times than the clicks, the absence of consistent task main effects suggests that the pianists synchronized their taps with the tone onsets in the music, not with their amplitude maxima or P-centers (contrary to observations by Vos, Mates, & Kruysbergen, 1995).

The timing profile of the computer-generated models and the average timing profiles of the tapping responses in Tasks 5 and 6 are illustrated in Figure 11. The correlations between the two tap-timing profiles are shown. They were a good deal higher than those among the corresponding asynchrony profiles (Figure 10), because of the much larger range of systematic variation. All pianists tended to underestimate the first of two successive lengthened IOIs in the model and to compensate afterwards; that tendency is seen most clearly in K.S.'s data. It is noteworthy that T.C. and M.S. were no less accurate than the other participants, even though they were presented with what must have seemed to them excessively modulated stimuli and even

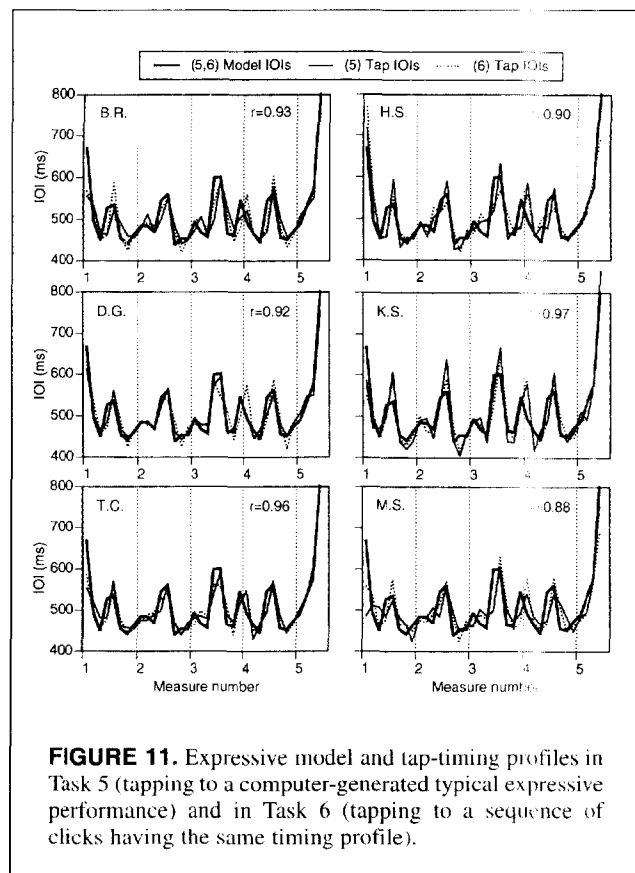


FIGURE 11. Expressive model and tap-timing profiles in Task 5 (tapping to a computer-generated typical expressive performance) and in Task 6 (tapping to a sequence of clicks having the same timing profile).

though they had received only minimal practice. Their accuracy may be attributed to the typicality of the timing pattern instantiated in the computer-generated performance. The finding that tracking the click sequence was no more difficult than tracking the musical model is impressive evidence for the role of a mental representation of the music in Task 6. Without such an auditory image, the tap-timing profiles in Task 6 presumably would have lagged one step behind the model profile (see Michon, 1967). In other words, they would have been completely reactive rather than largely predictive.

Tapping to One's Own Metronomic Performance (Task 9)

In Figure 12, the asynchrony profiles for Task 9 are depicted. Note that the scale is magnified relative to Figure 10. Again, only B.R. and M.S. showed large anticipation tendencies. One-way ANOVAs showed the positional variation in asynchronies to be highly significant for all 6 pianists. Although systematic timing variations in the metronomic models had arisen automatically in performance, the participants did not automatically predict them in their tapping; rather, they seemed to react to them.

The model and tap-timing profiles are shown in Figure 13, which also has a magnified scale compared with Figure 11. Because the models were single performances intended to be metronomic, not the average performances shown in Figure 6, the variation in their timing profiles was a combi-

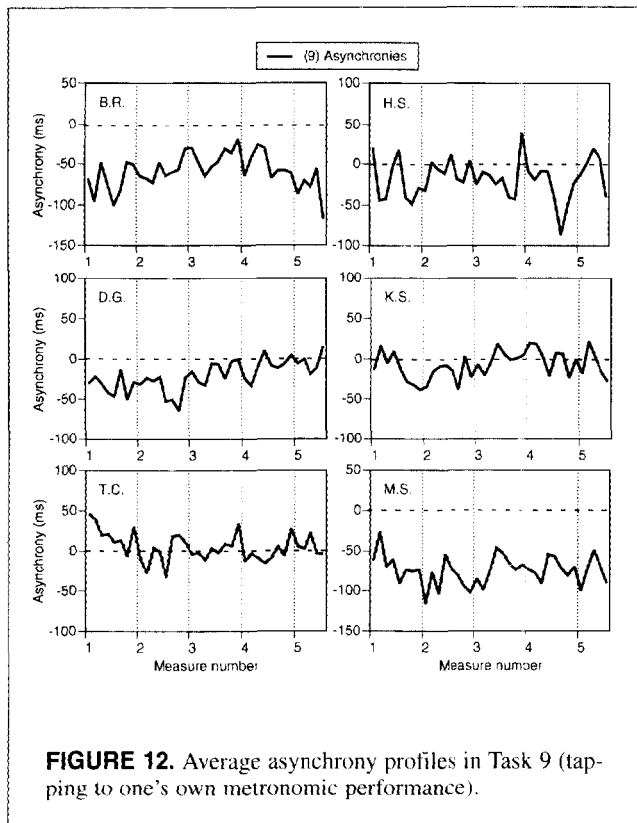


FIGURE 12. Average asynchrony profiles in Task 9 (tapping to one's own metronomic performance).

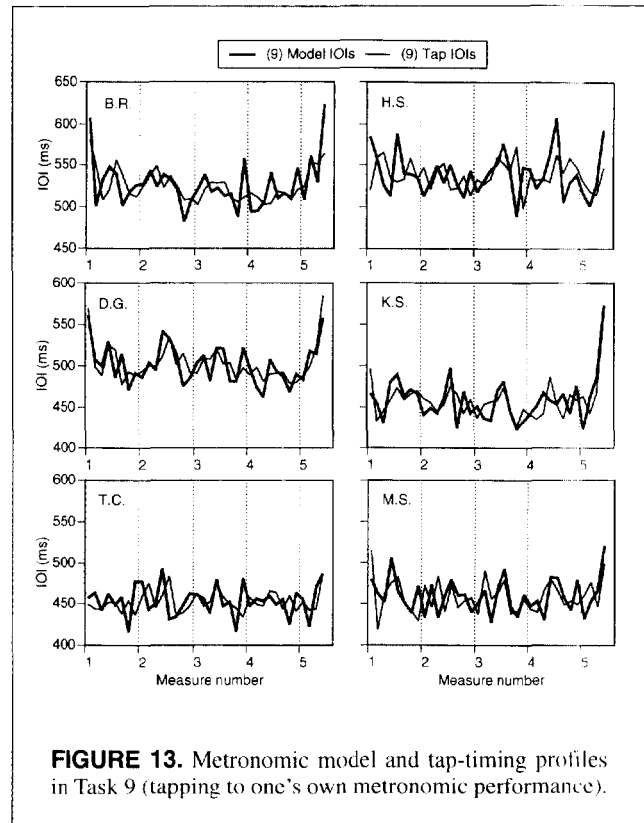


FIGURE 13. Metronomic model and tap-timing profiles in Task 9 (tapping to one's own metronomic performance).

nation of systematic (but unintended) and unsystematic variation. To some extent, therefore, Task 9 resembled tracking a randomly varying stimulus sequence (Hary & Moore, 1987; Schulze, 1992), except that the model was musical and therefore generated expressive timing expectations in the participants' minds. One can see that few of the small timing variations in the model profile were predicted accurately, and there is again some evidence for undershoot and subsequent compensation, as in Task 3. The negative Lag-1 correlation between the asynchrony profile (Figure 12) and the model profile (Figure 13) was significant for B.R. ($r = -.85$), H.S. ($r = -.76$), K.S. ($r = -.58$), and T.C. ($r = -.74$); it fell short of significance for D.G. ($r = -.37$) and M.S. ($r = -.25$). The pianists generally seemed to be unable to anticipate the timing variations in the model; that finding is consistent with the reduction or disappearance of systematic unintended timing variation in Task 10 (tapping to an imagined metronomic performance; see Figure 7).

Tapping to a Metronomic Computer Performance and to a Metronomic Sequence of Clicks (Tasks 11 and 12)

The asynchronies in Tasks 11 and 12 are shown in Figure 14. Task 11 duplicated an experiment (Repp, in press, Experiment 3) that demonstrated the presence of systematic timing variation in tapping to a metronomic musical model. That finding was replicated here, most clearly by D.G., K.S., and M.S. Those pianists also showed a clear reduction of systematic variation in Task 12. Nevertheless,

4 of the 6 participants did exhibit significant correlations between the asynchrony profiles in the two tasks, which suggests that systematic variations caused by musical imagery sometimes persisted even in the click synchronization task. However, the correlations for B.R. and T.C. seemed to result from overall trends rather than detailed timing patterns. Only for D.G. and K.S. was some similarity of pattern discerned. For those 2 pianists, then, imagining the music was sufficient to generate timing expectations that were reflected in their tapping to a metronomic sequence of clicks.

Two-way ANOVAs on the asynchrony profiles showed the position main effect to be highly significant for 5 pianists and still significant ($p < .01$) for H.S. The Task \times Position interaction was highly significant for D.G., K.S., and M.S. and was significant ($p < .004$) for B.R.; it was nonsignificant for H.S. and T.C. The task main effect was highly significant for K.S., M.S., and T.C., significant for B.R. ($p < .02$) and D.G. ($p < .03$), and nonsignificant for H.S. Separate one-way ANOVAs on the Task 12 asynchrony profiles showed the residual positional variation to be highly significant for 5 pianists; only for H.S. was it nonsignificant.

The tap-timing profiles for Tasks 11 and 12 and the correlations between them are shown in Figure 15. (The model profile may be imagined as a straight line at 500 ms.) Three pianists (B.R., D.G., and K.S.) showed moderately high, significant correlations between the two tasks, and T.C. evi-

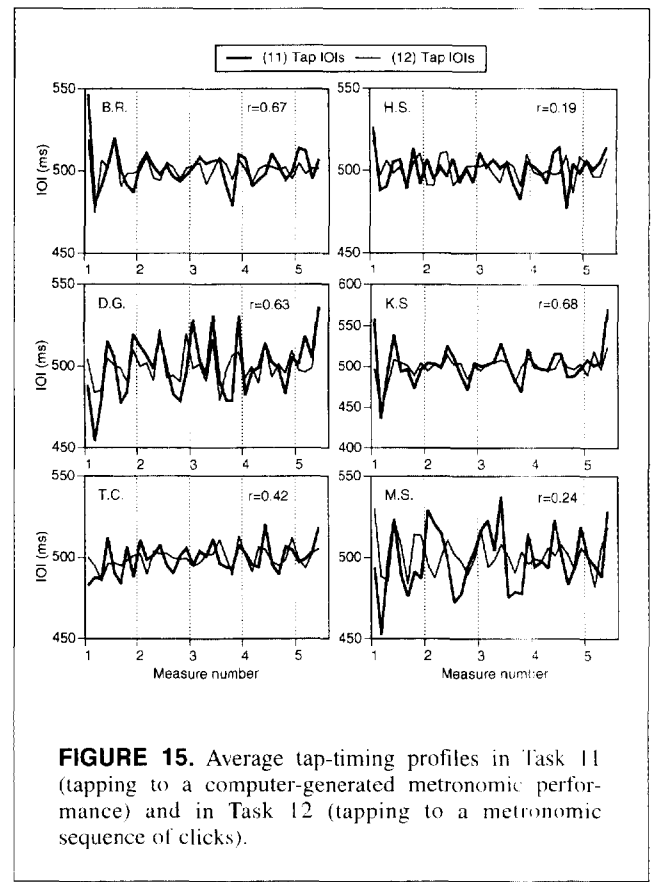
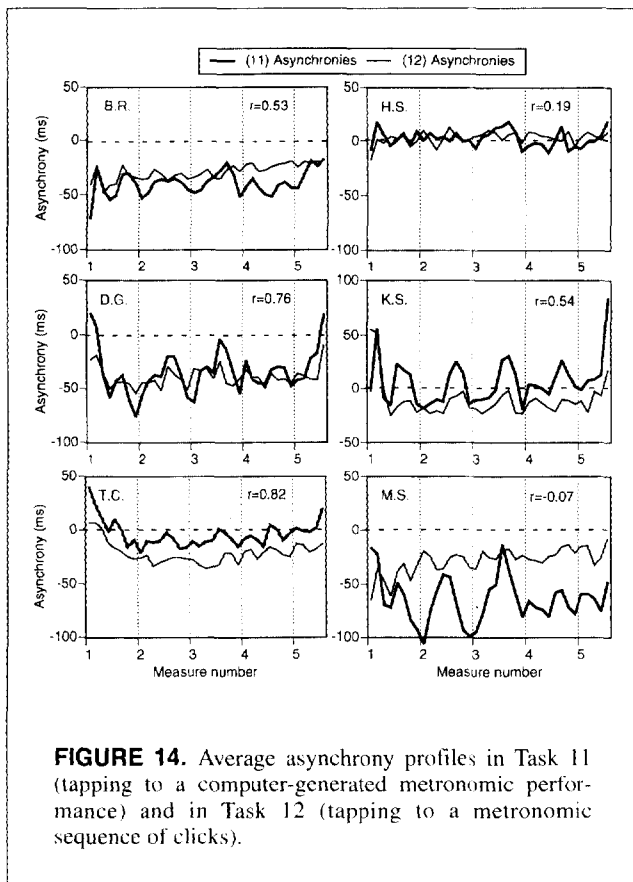


FIGURE 14. Average asynchrony profiles in Task 11 (tapping to a computer-generated metronomic performance) and in Task 12 (tapping to a metronomic sequence of clicks).

FIGURE 15. Average tap-timing profiles in Task 11 (tapping to a computer-generated metronomic performance) and in Task 12 (tapping to a metronomic sequence of clicks).

TABLE 4
Correlations Between Tasks 11 and 12
Tap-Timing Profiles and Task 1 Timing Profiles

Subject	Task 11	Task 12
B.R.	.61***	.36*
D.G.	.49**	.37*
T.C.	.37*	.30
H.S.	.52**	.22
K.S.	.70***	.37*
M.S.	.28	.59***

* $p < .05$, ** $p < .01$, *** $p < .001$.

denced a marginally significant correlation ($p < .05$). These correlations can no longer be attributed to overall trends, because the asynchrony profiles were effectively detrended by the differentiation that resulted in the tap-timing profiles. Thus, these results provide stronger evidence for systematic timing variation in tapping to metronomic clicks while imagining music. Moreover, there were significant correspondences between the tap-timing profiles and the pianists' expressive timing profiles in Task 1. Those correlations are shown in Table 4. They were not very high because the requirement of maintaining synchrony placed a constraint

on tap timing that did not exist in freely timed performance. Nevertheless, 5 of 6 pianists showed significant correlations between Tasks 1 and 11, and 4 between Tasks 1 and 12. The latter correlations were smaller than the former, except for M.S., who, paradoxically, showed the opposite pattern. These correlations suggest that the timing variation was the result of expectations of expressive timing that affected the timing of the motor response (Repp, in press).

Variability Across Repetitions

The variability data for Tasks 3, 5, and 6, summarized in Table 5, may be compared with the data in Table 2 (Tasks 1, 2, and 4). Because of the presence of a fixed model, no measure of basic tempo variability is provided here; although the average synchronization error exhibited some variation, that variation was not expected to scale with IOI duration, as variation in a freely established basic tempo would. Remarkably, however, the general pattern of results in Table 5 is quite comparable with that in Table 2, even though Tasks 3, 5, and 6 were externally paced. In other words, the externally paced tasks exhibited the same increase in variability of produced IOIs with IOI duration as the internally paced tasks. The size of the correlations, the magnitudes of the standard deviations at IOI = 500 ms, and the slopes of the regression lines were all in the same ballpark as previously, but there were no systematic differences in variability among the three tasks.

TABLE 5
Variability of Tap Interonset Intervals (IOIs) in Tasks 3, 5, and 6

Pianist	Task 3			Task 5			Task 6		
	(a)	(b)	(c)	(a)	(b)	(c)	(a)	(b)	(c)
B.R.	.74***	22	15.0	.83***	18	12.2	.71***	21	8.4
D.G.	.54***	21	5.9	.66***	25	12.8	.68***	25	14.0
T.C.	.27	15	3.2	.49**	21	6.8	.29	25	3.9
H.S.	.32	34	3.9	.62***	28	11.4	.67***	26	10.8
K.S.	.62***	32	6.9	.47**	29	4.5	.32	29	5.6
M.S.	.36*	27	3.7	.49**	24	5.1	.74***	29	16.8

Note. (a) Correlation between IOI duration and standard deviation; (b) estimated standard deviation (ms) at IOI = 500 ms; (c) slope of regression line ($\times 100$)

* $p < .05$, ** $p < .01$, *** $p < .001$.

TABLE 6
Average Lag-1 Autocorrelations of the Deviations
From the Model Timing Profile in Six Internally Paced Timing Tasks

Pianist	Task 3	Task 5	Task 6	Task 9	Task 11	Task 12
B.R.	-.16***	-.10**	-.30***	-.26***	-.07*	-.30***
D.G.	-.46***	-.18**	-.40***	-.23***	-.01	-.22***
T.C.	-.25***	-.36***	-.27***	-.40***	-.14*	-.21***
H.S.	-.30***	-.44***	-.20**	-.22***	-.28**	-.29***
K.S.	-.37***	-.35***	-.24***	-.36***	-.19***	-.13*
M.S.	-.40***	-.17***	-.32***	-.31***	-.07*	-.28***

Note: Asterisks (*) indicate significance based on t tests across the 10 trials.

* $p < .05$, ** $p < .01$, *** $p < .001$.

Lag-1 Autocorrelations

In the externally paced tasks, there were two possible ways of computing Lag-1 autocorrelations among tap IOIs: in terms of their deviations from the fixed model's IOIs or in terms of their deviations from the participant's average tap-timing profile (which, as we have seen, deviated systematically from the model). The first option seemed preferable because of the known invariance of the external standard. That invariance was expected to give rise to negative Lag-1 autocorrelations throughout, indicating automatic error correction or simply random motor variability. Table 6 shows those correlations, averaged over the 10 trials in each task. The correlations were indeed negative in all tasks and generally larger than the negative correlations in the internally paced tasks (Table 3). The negative correlations in the synchronization tasks with expressively timed models (Tasks 3, 5, and 6) contrast with the positive correlations obtained for 4 pianists in the internally paced expressive timing tasks (Tasks 1, 2, and 4). In addition, it is noteworthy that 5 of 6 pianists showed reduced negative correlations in Task 11, where significant tap-timing variation was elicited by a

metronomically timed music model. That finding suggests that the internal schedule of timing expectations elicited by the fixed external model was not invariant, but varied somewhat from trial to trial, at least in scale.

General Discussion

In the present study, pianists' control of timing in a variety of conditions was examined. The common situation of expressive performance (Task 1) was studied first. The results of that condition confirmed the well-known facts that skilled pianists have somewhat similar but individually different, often highly modulated timing profiles for music of the kind used here and that they are able to replicate their individual timing profiles with considerable accuracy. Unexpectedly, 2 pianists' timing profiles were relatively unmodulated, indicating that they spontaneously intended to play the music straight (as in Task 7). Even so, however, they showed systematic timing modulations qualitatively similar to those of the other 4 pianists, who played with great expression.

In Task 2, the pianists were deprived of auditory feedback. That had significant effects on expressive timing, but

the effects were so subtle and idiosyncratic as to seem practically negligible. All pianists were able to replicate their individual timing profiles with high accuracy; there was only a slight increase in overall variability. Those results suggest that expressive timing is generated from a stable internal representation of the music and does not depend importantly on real-time auditory feedback.

In Task 4, which required the participants to tap in synchrony with an imagined expressive performance, they were further deprived of kinaesthetic feedback from the piano keyboard. Nevertheless, the 4 pianists who had highly modulated timing profiles were able to tap them out fairly well on a single response key. To be sure, there were some larger discrepancies here, as well as a further increase in variability. Clearly, expressive timing is aided by the physical interaction with the musical instrument. Nevertheless, the present results demonstrate that a fair approximation of the expressive timing profile can be achieved from a mental representation of the music alone. The 2 pianists who played with little expressive timing to begin with tapped rather metronomically in Task 4, which confirms that their intention in Tasks 1 and 2 was to play straight. Their small but systematic timing patterns in those tasks presumably were unintended and derived from their gestural interaction with the piano keyboard.

The stability of the pianists' internally generated timing intentions was put to further tests in Tasks 3, 5, and 6. In Task 3, they were required to tap along with one of their own performances. Three of the 4 pianists with highly modulated timing profiles were remarkably successful in this task, which indicates that they were able to predict their own expressive timing patterns with considerable accuracy. There was a slight tendency to underestimate long IOIs, with subsequent compensation. That finding suggests that the pianists' internally generated timing was slightly less modulated than that of the external model. It is consistent with the results of Task 4 (tapping to an imagined expressive performance), which tended to show a reduction of temporal modulation relative to Tasks 1 and 2 (expressive performance). One pianist (B.R.) was clearly less successful in Task 3 than the others, reacting more to the input than actively predicting it. It was surprising that that task was the only condition in which the amateur was significantly inferior to the young professional-level artists. B.R. experienced Task 3 as somewhat challenging but was unaware of the extent of his inaccuracy, which could be predicted only partially from his Task 4 results.

The 2 pianists with only slightly modulated timing profiles, T.C. and M.S., were not much challenged in Task 3, which for them was similar to Task 9 (tapping to a metronomic model). In Task 5, however, they were presented with a highly modulated, computer-generated model. It is interesting that their synchronization with a typical timing profile, after only three practice trials, seemed just as accurate as that of the other pianists, and even B.R. did not do significantly worse here than the others. (Admittedly, he was

familiar with the model from his previous research.) Although the general tendency to underestimate long IOIs and compensate on the following tap, already observed in Task 3, was more pronounced here, all participants were able to predict the typical timing pattern to a considerable extent. That finding provides support for the idea that the typical profile (the average profile of many different performances) serves as a widely shared standard or norm that represents the most natural or default timing for the given music (Repp, 1997a, 1998c).

Task 6 contributed another interesting and novel result: All pianists were essentially just as accurate in tapping to a sequence of clicks that instantiated the typical timing profile as they were in tapping to the music in Task 5. Admittedly, they had the benefit of previous practice in Task 5. Nevertheless, the results found for Task 6 provide strong evidence (together with Task 4) that a timing profile can be generated from an internal representation of the music, without actually hearing the music. Without the aid of such an auditory image, it seems unlikely that participants would be able to remember and accurately predict the timing pattern of a series of 38 clicks after only a few presentations.

The six metronomic tasks followed up on two earlier findings—the occurrence of systematic timing variations in metronomic performance (Drake & Palmer, 1993; Palmer, 1989; Penel & Drake, 1998) and in tapping to a metronomic music model (Repp, in press). The first finding was strikingly confirmed in Task 7: The timing profiles of performances intended to be metronomic were much less modulated but nevertheless highly correlated with the expressive timing profiles of Task 1. The residual timing variation, then, seems to be unintended and obligatory, at least without extended practice in metronomic playing. It remains unclear whether the residual variation is the vestige of suppressed expressive intentions or, as Penel and Drake have argued, a compensation for perceptual distortions of temporal intervals, caused by the grouping structure of the music. Penel and Drake have also distinguished between obligatory and optional timing phenomena, corresponding to lower and higher levels of the hierarchical phrase structure, respectively. They found some evidence that only the former survive in “mechanical” performance. That issue may be moot with regard to the present short excerpt, which comprises only a single phrase (or less, according to some opinions), although the disproportionate reduction in the duration of the initial and final IOIs in metronomic playing is consistent with the hypothesis of Penel and Drake.

The results of Task 8 (metronomic playing without auditory feedback) provided strong evidence that the residual timing pattern does not depend on auditory feedback. If it is perceptually mediated (Penel & Drake, 1998), then the relevant perceptual distortions must be stored in auditory memory and be present in musical imagery.

However, the results of Task 10 (tapping to an imagined metronomic performance) suggest that the residual timing variation in Tasks 7 and 8 was largely caused by the

pianists' physical engagement with the musical instrument. Although some pianists showed significant timing variation in Task 10 and significant correlations between the Task 10 and Task 8 profiles, the similarities were not striking and seemed to rest mainly on lengthened initial and final IOIs. (Note also the results of T.C. and M.S. in Task 4, mentioned earlier.) Those findings, therefore, are problematic for the perceptual hypothesis of Penel and Drake (1998), for effects deriving from perception or memory should not depend on whether the timing pattern is executed on a piano or on a single response key. It seems more likely now that the timing profile of a metronomic performance has its origin in the pianist's physical interaction with the piano keyboard, either through a direct influence of motoric gestures on timing or indirectly, in that contact with the instrument may make it difficult to suppress expressive intentions completely.

The participants' ability to predict in their tapping the small but systematic timing variations in their own metronomic performance was tested in Task 9. To the extent that those variations were automatically generated from an internal representation of the music, one might have expected that they also would have been automatically predicted. The evidence for that prediction was not convincing: Participants seemed more to react to the model variations than to predict them. As pointed out earlier, however, that condition was somewhat problematic because the model, a single metronomic performance, contained a significant amount of unsystematic timing variation of about the same magnitude as the systematic timing variation, so its exact timing profile was indeed difficult to predict. Ideally, that condition should have been conducted with a model instantiating the average metronomic timing profile of Task 7, but that was not possible within the constraints of the experiment. However, the results are consistent with one possible conclusion from the results of Task 10, namely, that the residual timing profile of a metronomic performance does not originate from an internal representation of the music but rather from physical engagement with the piano keyboard.

An experiment reported by Repp (in press) was closely replicated in Task 11, with very similar results: When attempting to synchronize their taps with a truly metronomic music model, participants showed systematic timing variations. The tap-timing profiles exhibited considerable individual differences, but they also showed similarities and were significantly related to the individual and typical expressive timing profiles for the music. It seems that hearing the music elicits timing expectations that are involuntarily acted out in the finger taps.

In Task 12, an important control condition was presented: Would the systematic timing variations disappear when participants tapped to metronomic clicks while merely imagining the music? The results were not entirely clear-cut; several pianists still showed traces of the previous variation even in tapping to clicks. On the whole, however, the systematic variation was much reduced, and we may conclude that it arose largely from perceiving the music auditorily.

That conclusion also agrees with the result of an experiment reported in Repp (1998d); in that experiment, participants tried to detect timing deviations in an otherwise metronomic sequence of clicks while imagining the music in synchrony with the clicks. Imagining the music had no systematic effects on the detectability of the timing deviations, whereas detecting timing deviations in a metronomic performance of the music was subject to very large bias effects (Repp, 1998d, 1998e, in press). The tentative conclusion, then, is that an internal representation of the music supports intentional expressive timing (Tasks 1–6) but is not the principal origin of unintentional systematic timing variations in metronomic tasks (Tasks 7–12), which seem to arise from real-time perceptual processing or motor activity.

Analyses of the relationship between (average) IOI duration and IOI variability across the 10 repetitions in each expressive task replicated Repp's (1997b) finding of a roughly linear increase in variability. That increase was observed equally in internally paced (Tasks 1, 2, and 4) and in externally paced (Tasks 3, 5, and 6) tasks; it appears to reflect a steady increase in the variability of an internal timekeeper with the duration of the interval being timed, regardless of whether that interval is freely timed or intended to be predictive of an external event. Such an increase would be the natural result if each interval were timed by accumulating a number of smaller intervals, each with a nonzero variance, such as might be supplied by a central pacemaker (see, e.g., Treisman, Faulkner, & Naish, 1992).⁵ The linear nature of the increase in the present data is sufficient evidence that the high variability of long IOIs does not spill over into adjacent short IOIs in the form of compensation effects. Rather, it appears that each IOI is timed anew from its beginning. The slow rate of the present stimuli and action sequences (about 2/s) probably precluded any higher level hierarchical timing control that could have resulted in compensatory effects. Higher level timing control would seem to be effective only when its variability does not substantially exceed that of lower level timing control, and that situation occurs only when the lower level rate of events exceeds 3–4/s. A more detailed analysis of the covariance structure (see Vorberg & Wing, 1996) of the present performances was beyond the scope of this article.

Finally, an interesting tendency was revealed by an analysis of the Lag-1 autocorrelations among the deviations from the average timing profile (internally paced tasks) or model profile (externally paced tasks). As expected, those correlations were significantly negative in all synchronization tasks, presumably because of a corrective mechanism that minimized the synchronization error. They were also negative in the internally paced metronomic tasks and in the internally paced expressive tasks for those 2 pianists who played nearly metronomically. For the 4 pianists who played with much expressive timing, however, the Lag-1 autocorrelations were on the positive side. That finding suggests a variable internal timing plan, where the variability is not random but is coherent, taking the form of a multiplicative

scaling factor (i.e., trial-to-trial variations in basic tempo or magnitude of the timing deviations, or in both). Such coherent variation would tend to introduce positive covariation among adjacent IOIs, as was also observed by Repp (1997b). There was an interesting reduction in the size of the negative Lag-1 autocorrelations in Task 11, suggesting that exposure to metronomically timed music may invoke timing expectations that are themselves coherently variable. Coherent variation, whether intended or not, may be regarded as a hallmark of internal or external structural control.

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NOTES

1. Three sources of inaccuracy in the data should be mentioned; they were not considered serious problems, however. First, it was known from earlier output measurements that MAX, for reasons that are still not fully understood, plays MIDI instructions at a rate 2.4% faster than specified and also times external actions at a correspondingly slower rate. That is, a 500-ms IOI was realized as 488 ms, and a 488-ms played or tapped IOI was registered as 500 ms. For simplicity, all IOIs are reported in terms of the values specified or registered in MAX, although the actual values should be understood to have been uniformly shorter by 2.4%. Apart from that constant scaling factor, MAX was highly accurate in timing outgoing or incoming information. Second, in the tapping tasks, quantization noise was introduced by the Macintosh keyboard, which was scanned by the computer only 60 times a second, or every 16.7 ms. For registered key presses, that scanning rate implies a rectangular distribution of random delays with a mean of 8.3 ms and a variance of about 23.2 ms². Because the absolute magnitude of the average synchronization error was not of particular interest here, the average delay was considered negligible; moreover, it was counteracted by the fact that a key press was electronically registered some time before the key touched bottom. The delay variance, too, was considered insignificant, because it was about an order of magnitude smaller than the total observed variance in the various tasks. No correction was applied to the data, because that would have changed standard deviations by less than 1 ms.

A third source of inaccuracy was caused by a flaw in the construction of the computer-generated musical models in the synchronization tasks (Tasks 5 and 11), which was discovered only after completion of the experiment. It resulted in a small temporal jitter (range = 6 ms), caused by MIDI transmission delays, which was superimposed on the expressive timing profile of the Task 5 model and on the metronomic timing of the Task 11 model. That problem was potentially worrisome only in Task 11. However, Repp (in press, Experiment 3) conducted a very similar experiment in which the problem was corrected and in which very similar results were obtained, suggesting that the jitter had no major effects on synchronization accuracy.

2. Amusingly, H.S. played the excerpt in E-flat major instead of E major, which was not noticed until the data analysis stage. The previous year, when he had played the same excerpt in a different experiment, he had done precisely the same thing!

3. In this article, possible effects of auditory feedback deprivation on other performance aspects, such as expressive dynamics and pedaling are not addressed. A comprehensive analysis of these data is presented in Repp (1998b).

4. The effects are mostly subtle and difficult to interpret. They could be caused in part or entirely by the presence of temporal jitter in the music model but not in the click model (see Note 1), but in that case the pattern of differences between the Task 5 and Task 6 asynchrony profiles should be similar across pianists, which it did not seem to be.

5. Although such a model would seem to predict a linear increase of the variance rather than the standard deviation with IOI duration, at least one group of researchers has proposed a pace-maker model that predicts a linear increase of the standard deviation (Gibbon, Church, & Meck, 1984). That model is also consistent with most recent studies in the literature (see, e.g., Collyer et al., 1997; Ivry & Hazeltine, 1995; Peters, 1989), although Vorberg and Wing (1996) consider the issue unresolved.

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