NOTE: The music examples for this article may be found at http://www.macarthur.uws.edu.au/marcs/ajp_music.html or a DAT or cassette tape may be requested from the author.

1148.

Relationships Between Performance Timing, Perception of Timing Perturbations, and Perceptual–Motor Synchronisation in Two Chopin Preludes

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In earlier studies using relatively short musical excerpts, a close relationship was found between expressive performance timing and positional variations in the detectability of local timing perturbations in an otherwise evenly timed computer rendition of the music. Weaker but significant relationships held between each of these measures and positional variation in the accuracy of synchronised finger tapping with the evenly timed music. These findings suggested that musical structure induces temporal expectations that are reflected in conscious perception and in motor control. In this study, extended between-task correlations were examined in two longer piano pieces, Chopin's Preludes No. 15 (Bars 1–19) and No. 6 (complete). In addition to perceptual detection and perceptual-motor synchronisation tasks, pianists were recorded playing the music in three ways: with normal expression, metronomically (without the aid of a metronome), and in synchrony with a metronome. The (intended or unintended) timing patterns of these three performance styles were quite similar and showed the predicted significant relationships with the patterns of detection and synchronisation accuracy. However, the correlations were weaker than expected, which suggests that additional, task-specific factors played a role.

When small local deviations from temporal regularity are introduced in a computer-controlled, evenly timed performance of piano music, their conscious detectability depends strongly on their position within the musical structure (Repp, 1992c, 1998e, 1999b). In particular, it seems to depend on the melodic-rhythmic grouping structure of the music: the lengthening of a tone inter-onset interval (IOI) — an IOI increment, perceived as a hesitation — is usually more difficult to detect at the end of a group than at its beginning or centre. Melodic-rhythmic grouping is also the major structural factor influencing expressive timing in music performance, with lengthening at the ends of groups being very common (Repp, 1992b; Todd, 1985). As a consequence, Repp (1992c, 1998e, 1999b) found a strong negative correlation between variations in the detectability of IOI increments in evenly timed music (average percent correct as a function of position in the music: the *detection accuracy profile*) and the relative durations of the corresponding IOIs in expressive performances of the same music (average IOI duration as a function of position in the music: the *expressive timing profile*). This relationship appears to reflect timing expectations (Repp, 1998c, 1998e) or, equivalently, distortions of perceived relative durations (Penel & Drake, 1998; Repp, 1998a) induced by perception of (and memory for) musical structure, and of melodic-rhythmic groups in particular.[1]

This result is clearly related to another finding, namely that pianists, when asked to play "metronomically" or "mechanically" (i.e., with perfectly even timing, but without the aid of a metronome), unintentionally produce systematic residual timing variations that are quite similar in pattern to the usually much larger timing variations found in expressive performance (Penel & Drake, 1998; Repp, 1999a; see also Behne & Wetekam, 1993; Clarke & Baker-Short, 1987; Drake & Palmer, 1993; Palmer, 1989; Seashore, 1938/1967). Thus, the *metronomic timing profile* is positively correlated with the expressive timing profile and therefore should also be negatively correlated with the detection accuracy profile for IOI increments, perhaps even more highly than the expressive timing profile because the metronomic timing profile, like the detection accuracy profile, reflects variation that is not under conscious control. Although this correlation has not been reported previously, some relevant data are already available: expressive and metronomic performance timing profiles for the opening of Chopin's Etude in E major (Repp, 1999a) correlate equally highly ($r = -0.77$, $p < .001$) with the detection accuracy profile for the same musical excerpt (Repp, 1999b, Exp. 1).

Recently, yet another related phenomenon has been observed. Repp (1999b) asked participants to tap a response key in synchrony with evenly timed piano music. (See also Repp, 1999a, in press.) The average asynchronies and inter-tap intervals were found to exhibit small but systematic deviations from regularity as a function of position in the music. Thus, they exhibited an *asynchrony profile* and a *tap timing profile*. These profiles were positively correlated with the expressive timing profile and negatively correlated with the detection accuracy profile for IOI increments. This result suggested that temporal expectations induced by perception of (and memory for) the musical structure affect not only conscious perception but also the automatic control processes that govern the timing of a synchronised motor response, possibly by modulating the period of a central timekeeper governing both tasks. However, the correlations were a good deal weaker than the one between the expressive timing profile and the detection accuracy profile, which made the interpretation of the synchronisation results somewhat tentative.

One reason for the small size of these correlations could be that the synchronisation task imposes a constraint that is not present in expressive or even metronomic performance, namely to stay in synchrony with an external, rigidly timed sequence of sounds. Synchronisation requires compensation for asynchronies caused by response variability (i.e., error correction: see Pressing, 1998, in press), and this compensation

This research was supported by NIH Grant MH-51230. Thanks are due to Lisa Robinson and Paul Buechler for extensive assistance, and to Amandine Penel and two anonymous reviewers for helpful comments on the manuscript.

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necessarily attenuates and contaminates any tendencies to systematically deviate from synchrony. The asynchrony and tap timing profiles might be more closely related to the timing pattern of a performance produced in synchrony with a metronome (a *synchronised timing profile*), which is subject to the same constraint. It appears that the timing of such synchronised performances has not been investigated previously, and so this was one novel aspect of the present study.

The present research went beyond previous work not only by including three different performance conditions (expressive, metronomic, and synchronised) but also by using musical materials of substantially longer duration. The musical excerpts in previous studies of the relationship between the detection accuracy and expressive timing profiles were Bars 1–8 of the minuet from Beethoven's Sonata in E-flat major, op. 31, No. 3 (Repp, 1992c: Exp. 1), Bars 1–8 of Schumann's "Träumerei", op. 15, No. 7 (Repp, 1992c: Exp. 2), and Bars 1–5 of Chopin's Etude in E major, op. 10, No. 3 (Repp, 1998a, 1998c, 1998e: Exp. 1, 1999b), as well as some simpler materials (Repp, 1992a, 1995, 1998e: Exps. 2–5). Synchronised tapping to music has been investigated only with the Chopin Etude excerpt (Repp, 1999a, 1999b, in press). The present two experiments employed one substantial excerpt (Bars 1–19 of Chopin's Prelude No. 15) and one complete piece (Chopin's Prelude No. 6), respectively, which were 4 to 6 times as long as previous materials. As in previous studies, the choice of these materials was constrained by the methodological desiderata of (a) a fairly slow tempo, (b) note onsets at regular intervals, and (c) large expressive timing variations in performance. Each experiment included detection and synchronisation tasks in addition to the three performance conditions. This made it possible to investigate the relationships between six different profiles: expressive, metronomic, and synchronised timing; detection accuracy; asynchronies; and tap timing. In Experiment 2, moreover, there were three different detection accuracy profiles and two metrical levels, as will be explained later.

The specific predictions were the following:

1. There should be systematic variation in all profiles, not only in the expressive timing and detection accuracy profiles (which always exhibit large variation), but also in the metronomic timing, asynchrony, and tap timing profiles, and even in the synchronised timing profile, which was investigated here for the first time.
2. The metronomic timing profile should show a strong positive correlation with the expressive timing profile, as in previous studies.
3. The synchronised timing profile (unintentional, constrained variation) should show a weaker positive correlation with the expressive timing profile (intentional, unconstrained variation) than with the metronomic timing profile (unintentional, unconstrained variation).
4. The detection accuracy profile for IOI increments should show a strong negative correlation with the expressive timing profile, and perhaps an even stronger negative correlation with the metronomic timing profile. It also should correlate with the synchronised timing profile, though perhaps not as strongly.
5. The asynchrony and tap timing profiles (which are positively correlated because the latter is the first difference of the former, plus a constant) should show moderate positive correlations with the expressive and metronomic timing profiles, but a higher positive correlation with the synchronised timing profile, which shares the constraint of referential control (Pressing, in press). They also should be negatively correlated with the detection accuracy profile.

EXPERIMENT 1
Methods

The Music

The musical excerpt consisted of Bars 1–19 of Frédéric Chopin's Prelude in D-flat major, op. 28, No. 15 (popularly known as the "Raindrop Prelude"). The score is shown in Figure 1. The melody, played by the right hand, is accompanied by pulsating eighth notes interspersed with dyadic or triadic chords, played by the left hand. There are only two moments (at the beginnings of Bars 3 and 7) where an inner voice emerges briefly, and these are also the only places where the otherwise monophonic right hand typically takes over some of the left-hand notes for convenience. The excerpt begins with a four-bar phrase that is repeated almost literally in Bars 5–8. A new, somewhat abbreviated four-bar phrase follows in the related key of A-flat major that turns into the minor mode in Bar 11. This phrase, too, is repeated immediately with some changes, including an extended upbeat in Bar 12 and a harmonic modulation leading to B-flat minor in Bar 16. Bars 16–17 represent a contraction (a concatenation of the initial and final bars) of the preceding four-bar phrase, and Bars 18–19 are like an afterthought that fades away and leads back to the tonic of D-flat major. Bars 20–27, which complete the initial section of the tripartite composition, are similar to Bars 1–8 and therefore were not included in the experiment. The excerpt stopped at the end of Bar 19, just before the return to the tonic, so that the end of one presentation created a desire to hear the beginning of the next presentation.

Performances

Participants. Eight pianists with advanced skills participated. They included two individuals with artist's diplomas in piano performance and one with a master's degree in composition from the Yale School of Music, one graduate student of music theory who was writing a dissertation on Chopin, three talented undergraduate students, and one seasoned amateur (the author). The performances of one additional participant were considered unsatisfactory and were excluded from analysis. The participants knew they had to be able to play the

Figure 1
Bars 1–19 of Prelude No. 15 in D-flat major, from op. 28 by Frédéric Chopin (Wiener Urtext Edition, Schott/Universal Edition, 1973; reproduced by permission).

music well after only minimal rehearsal. Their payment, in view of the expertise required, was $25/hour.

Procedure. The pianists played on a Yamaha Clavinova CLP-611 digital piano, monitoring the sound ("Piano 1") over earphones. Their performances were recorded in MIDI format by a Macintosh Quadra 660AV computer running MAX software.[2] After a brief warm-up and practice period, the pianists played Bars 1–19 of the music three times with expression from the score (Figure 1), at their preferred tempo. (The performances included the downbeat of Bar 20, but the final IOI was disregarded in data analyses because it did not occur in the detection and synchronisation tasks.) Subsequently, the metronome of the digital piano was set to a rate corresponding approximately to that of the eighth notes in the expressive performances. (Normally, a metronome would be set at the rate of the quarter notes, which represent the metrical beats.) The pianists then played the music three more times, trying to synchronise their note onsets with the metronome ticks. The metronome ticks were not recorded. Finally, the metronome was turned off, and a set of three performances was recorded in which the pianists tried to play metronomically (i.e., as if playing in synchrony with a metronome). This order of conditions was the same for all pianists. The metronomic playing condition was deliberately made to follow the synchronised playing condition in order to discourage residual expressive timing in metronomic playing.

Analysis. The MIDI data were saved in text format and imported into a spreadsheet program. There, the onsets of the *primary notes* were identified and labelled. A primary note was defined as the one with the highest pitch in each eighth-note position; that is, it was either a melody note or the highest accompaniment note. Sixteenth notes, grace notes, and the ornamental septuplet in Bar 4 were ignored. The inter-onset intervals (IOIs) between the primary notes were then computed, averaged across the three performances in each condition, and finally averaged across the eight participants to yield an average timing profile for each condition. (The adjective "average" will be omitted henceforth when referring to profiles.) All IOIs represented the same metrical subdivision in the score (i.e., eighth notes), so that any systematic variation in their duration was of expressive origin.

Detection Task

Stimuli. Bars 1–19 were extracted from a fine performance of the prelude which had been given several years ago on a Yamaha Disklavier upright piano by an advanced graduate student at the Yale School of Music and had been recorded in MIDI format. It still sounded very nice when played back on the Roland RD-250s digital piano in the author's laboratory, despite the somewhat synthetic sound; only soft pedal instructions had to be removed from the MIDI file because they caused abnormally large changes in volume on the digital piano. This expressively timed version was not actually used in the experiment but is included as Sound Example 1 to give the reader an opportunity to appreciate the nature and extent of expressive timing in a good performance of this music.

For the experiment, the expressive timing was removed, leaving all other performance aspects (keypress velocities, asynchronies among simultaneous notes, overlaps among successive notes, pedalling) essentially unchanged. This transformation was carried out in a spreadsheet program into which the recorded MIDI instructions had been imported as a text file.[3] First, the primary notes were identified and the IOIs among them were calculated. Then the temporal intervals between successive MIDI events within each eighth-note IOI (additional note onsets, note offsets, pedal depressions, and pedal releases) were expressed as proportions of the total IOI duration. All IOIs were then set to a constant value of 480 ms, which corresponded to the average IOI duration in the excerpt, and the inter-event intervals within each IOI were re-computed as proportions of this new duration. Finally, new onset times for all events were obtained by cumulating all inter-event intervals. The result was a performance that sounded very similar to the original but was evenly timed (Sound Example 2).

For the detection task, lengthenings of single IOIs were introduced in various positions of the evenly timed performance. Each lengthening was implemented locally by the method just described, so that all inter-event intervals within the lengthened IOI were lengthened proportionally. On the basis of pilot observations which suggested that the task was more difficult than in earlier experiments with shorter excerpts, three increment sizes were decided on, representing 14%, 12%, and 10% of the baseline IOI (i.e., about 67, 58, and 48 ms, respectively). There are 151 IOIs in the excerpt (19 x 8 – 1, because Bar 19 has only 7 IOIs). In the course of one block of 10 trials, each of these 151 IOIs was lengthened once by the same amount. Each trial thus contained about 15 detection targets, which were spaced quasi-randomly but always with at least five unchanged IOIs intervening. The three increment sizes led to three blocks of 10 trials each. A trial containing 14% increments is presented as Sound Example 3.

Participants. Fourteen volunteers aged 14 to 29, mostly summer college students, were recruited through advertisements on Yale campus and were paid $8/hour. Although musical training was not a requirement, all participants had had some musical instruction, ranging from 3 years of violin to 21 years on several instruments combined. One participant's responses were excluded because he seemed to be guessing randomly.

Procedure. The participant sat in front of a computer monitor and listened to the stimuli binaurally over Sennheiser HD540 II earphones. For familiarisation, the evenly timed version of the excerpt was played once, followed by a version that contained IOIs lengthened by 20%. This was followed by the three blocks of 10 experimental trials each, each lasting about 15 minutes and separated by breaks. Whenever the participant detected a deviation from temporal regularity (i.e., a momentary hesitation), he or she was to quickly press the space bar of the computer keyboard. The increment size in the first block was 14% of the baseline interval (though it was 12% for one participant). The increment sizes in the subsequent blocks were chosen according to the participant's performance on the preceding block, so as to maintain a reasonable average percentage of hits. The best listeners received blocks with 14%, 12%, and 10% increments, respectively; the poorest ones listened three times to the block with 14% increments; others received one block of 14% followed by two of 12%, or two of 14% followed by one of 12%. The goal was to stay as close as possible to an average hit rate of 50%, to avoid floor and ceiling effects in the detection accuracy profiles; individual differences in overall accuracy were of no interest. Actually, the task proved to be more difficult than expected, despite the relatively large increment sizes, but floor effects were largely avoided. Stimulus presentation and data collection were controlled by a MAX patcher (i.e., program).

Analysis. Responses occurring earlier than 200 ms or later than 1000 ms after the onset of the primary note terminating a lengthened IOI were considered false alarms. False alarms were not analysed. The number of hits (maximum = 3) was determined for each of the 151 positions in the music, combining the data from all three blocks. These numbers were then added up across the 13 participants and converted into percentages to yield the detection accuracy profile.

Synchronisation Task

Stimuli. The evenly timed performance described above was the single stimulus.

Participants. Six of the participants in the detection task returned for the synchronisation task, and five additional participants were newly recruited. The author also performed the task, so that there were 12 participants in all. Payment was $8/hour.

Procedure. The session began with finger tapping to 30 repetitions of a different, shorter musical excerpt (Repp, 1999b: Exp. 3), which took about 10 minutes. Participants then tapped in synchrony with one presentation of the Chopin Prelude excerpt for practice. They tapped with their index finger on the "enter" key, located in the lower right-hand corner of the Macintosh computer keyboard. One left-handed participant tapped on the "~" key, located in the upper left-hand corner of the keyboard. Participants turned their chair 90 degrees, so that their lower arm rested on the table next to the keyboard. They were instructed to keep their finger in contact with the key and to synchronise their key presses with the onsets of eighth notes in the music. Three blocks of 10 experimental trials were then presented, each lasting about 15 minutes and separated by breaks. A MAX patcher controlled presentation and data collection.

Analysis. Taps occasionally did not register, due to either keyboard malfunction or, more likely, participant fatigue (152 taps per trial!). Since there were 30 trials, however, occasional missing data had little impact. Blanks were inserted so that trials with missing taps were aligned with the other trials. Asynchronies were computed by subtracting the primary note onset times in the stimulus (which occurred in increments of 480 ms) from the participants' key depression times. The asynchronies were subsequently averaged across the 30 trials and the 12 participants, so that each value was based on close to 360 observations. Inter-tap intervals were computed as the first difference of the asynchronies plus 480 ms and were similarly averaged.

Results and Discussion

The six profiles are shown in Figure 2. The melodic line is shown in musical notation above the figure for orientation.[4] To save space, the data for Bars 5–8 and 13–16 have been overlaid onto those for the structurally very similar Bars 1–4 and 9–12, respectively. The similarity of these overlaid portions of the profiles provides an index of the internal consistency or reliability of the results. The relevant correlations are summarised in the main diagonal of Table 1; they are all highly significant and of satisfactory magnitude. (Note also that Bars 17–18 are rhythmically equivalent to Bars 11–12 and 15–16.) Intercorrelations among the different profiles are likewise shown in Table 1.

Figure 2a displays the expressive timing profile.[5] As expected, it shows large and systematic deviations from even timing. The final IOI of Bar 4 has been omitted from the graph and from the correlations reported in Table 1 because of its exceptionally long duration (854 ms), due to the septuplet ornament that occurs at that point in the melody. The overlaid portions of the profile are extremely similar.[6] The shape of the expressive timing profile can be characterised as being largely due to a slowing of the local tempo in the vicinity of bar lines (i.e., immediately before metrical downbeats), as well as on the downbeats themselves, which are always melody notes. Bars 10, 11, 14, 15, and 17 contain sequences of melodic eighth notes followed by a long note, and their four IOIs show a characteristic trough shape, with the inner IOIs being much shorter than the outer ones. (A lengthening of short melody notes preceding or following a long note is often observed; see Gabrielsson, Bengtsson, & Gabrielsson, 1983; Drake & Palmer, 1993.) There is extra lengthening at the beginning and end of the piece.[7]

The metronomic timing profile is shown in Figure 2b. Naturally, this profile is much less varied than the expressive timing profile. (Note the smaller range of the scale on the ordinate.) Nevertheless, it shows reliable deviations from regularity (the overlaid data are significantly correlated), both at a local level and also more globally in terms of a drift towards a slightly faster tempo during Bars 9–17. As predicted, the metronomic timing profile is significantly correlated with the expressive timing profile. This is still true when the extra-long initial and final IOIs are omitted, $r(146) = .54$, $p < .0001$.

The synchronised timing profile can be seen in Figure 2c. Due to the presence of an explicit metronome beat, there is no slow drift here. However, there are still systematic deviations from evenness. Indeed, the synchronised profile is significantly correlated with both the metronomic and the expressive timing profile. Without the initial and final data points, these correlations decrease to .57 and .32, respectively, but they remain highly significant. The synchronised timing profile is more closely related to the metronomic timing profile than to the expressive timing profile, as predicted, whereas the metronomic timing profile is equally similar to the expressive and synchronised timing profiles.

The detection accuracy profile is shown in Figure 2d. As expected, there was large variation in the detectability of IOI

Table 1
Correlations Among the Profiles Shown in Figure 2 (df = 144 to 149)

Profile	ET	MT	ST	DA	AS	TT
Expressive timing (ET)[a]	.86***					
Metronomic timing (MT)	.63***	.69***				
Synchronised timing (ST)	.41***	.62***	.59***			
Detection accuracy (DA)	−.40***	−.26**	−.30**	.63***		
Asynchronies (AS)[b,c]	−.01	.04	.19	−.51***	.67***	
Tap timing (TT)[c]	.10	.28**	.38***	−.25*	.38***	.68***

Note. The entries in the main diagonal represent the correlations between the overlaid portions of each profile (df = 57 to 62).
[a] One data point omitted (exceptionally large value). [b] Shifted by one position to the left. [c] Two initial data points absent (because tapping started on the second beat) and the next three data points omitted (to avoid the "tuning-in" period).
* $p < .01$. ** $p < .001$. *** $p < .0001$.

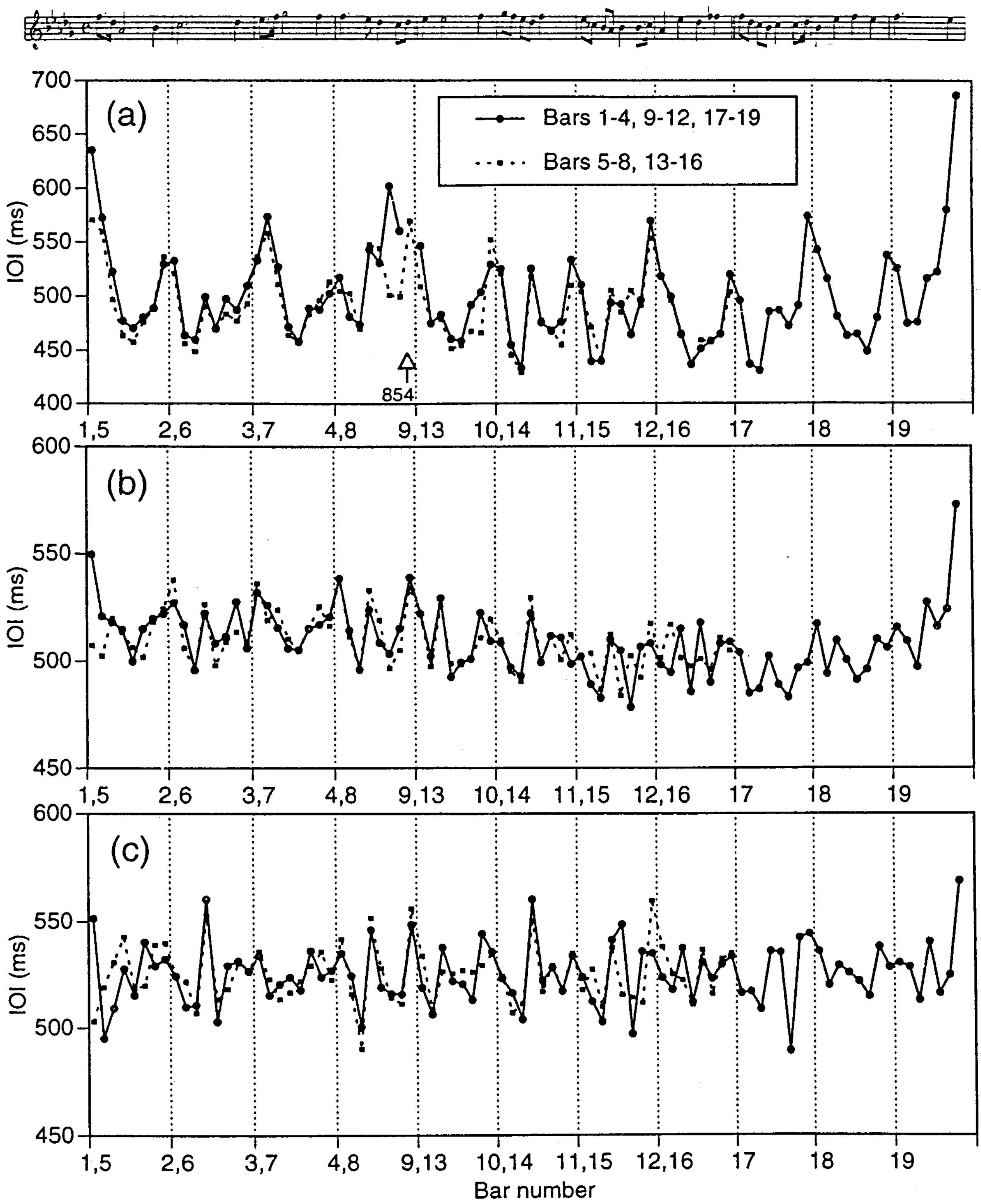

Figure 2 (a, b, c)
Data profiles of Experiment 1: (a) expressive timing profile, (b) metronomic timing profile, (c) synchronised timing profile.

increments, with average scores ranging from 0 to over 90% correct. The correlations of the detection accuracy profile with the performance timing profiles are negative, as predicted. However, while significant, they are much weaker than expected on the basis of earlier findings. Moreover, they do not confirm the prediction that the detection accuracy profile would be more closely related to the metronomic than to the expressive timing profile.

The detection accuracy profile shows several features that may account for the low correlations. First, detection accuracy was extremely poor from the middle of Bar 17 to the end, for unknown reasons. Second, detection scores were generally lower in melody note positions (i.e., where the IOI was initiated by a melody note) than in accompaniment note positions; the average scores were 27.6% and 40.9%, respectively. High scores in melody note positions occurred only at the begin-

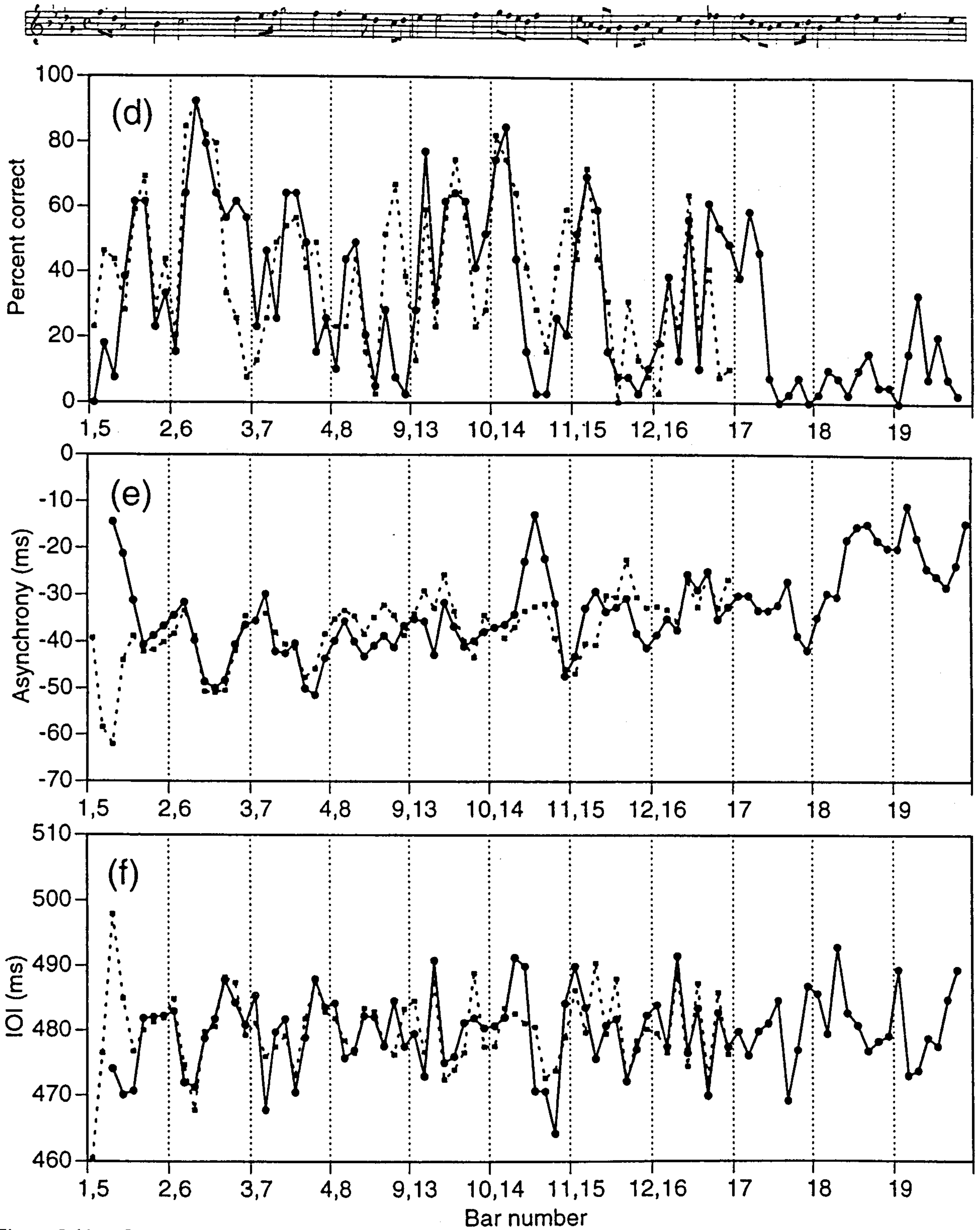

Figure 2 (d, e, f)
Data profiles of Experiment 1: (d) detection accuracy profile, (e) asynchrony profile, (f) tap timing profile.

nings of the eighth-note runs in Bars 10, 11, 14, 15, and 17. Third, detection scores plummeted dramatically during melodic eighth-note runs.

The second of these results suggests a role of relative intensity, for melody tones were of course louder than accompaniment tones. Earlier research has shown that temporal intervals tend to be perceived as relatively shorter when they follow a loud sound than when they precede it (Tekman, 1995, 1997; Woodrow, 1909). Therefore, IOIs initiated by melody tones may have been perceived as shorter than IOIs terminated by melody tones (most of which were initiated by accompaniment tones), so that increments were more difficult to detect in the former than in the latter. Clearly, it is not just the loudness of the primary tone initiating an IOI that matters: the correlation between its keypress velocity and detection accuracy was nonsignificant ($r = .05$, $df = 149$). The relevant variable is the intensity difference (first minus second) between the two tones delimiting an IOI, as already noted by Repp (1992c, 1998e): increments were harder to detect the louder the first tone was relative to the second ($r = -.34$, $df = 149$, $p < .001$). Moreover, this relationship was found to be specific to IOIs initiated by melody tones, where the second tone was usually softer than the first ($r = -.65$, $df = 70$, $p < .0001$); it was absent in IOIs initiated by accompaniment tones ($r = .17$, $df = 77$, *ns*). Melody IOIs could be further subdivided into those that were terminated by a melody tone and those that were terminated by an accompaniment tone. Only the detection scores for within-melody IOIs (i.e., in melodic eighth-note runs) showed a significant relationship with velocity difference ($r = -.69$, $df = 21$, $p < .001$).[8] Thus, the decline in detection accuracy during eighth-note runs was related to the relative intensities of successive melody tones. When melody-accompaniment and accompaniment-melody IOIs were combined, a significant correlation of detection accuracy with velocity difference emerged also ($r = -.44$, $df = 78$, $p < .001$). Although these correlations do not prove a causal relationship between intensity difference and increment detectability, they are consistent with such a relationship. Of course, intensity differences are part and parcel of the musical structure, for they reflect differentiation of voices, rhythmic grouping, melodic pitch contour, and meter, among other things.

The asynchrony profile is shown in Figure 2e. The negative asynchronies are typical of synchronisation tasks; that is, the taps anticipated the note onsets (see, e.g., Aschersleben & Prinz, 1995). The overlaid portions of the data diverge greatly at the beginning. (The initial two data points are missing because tapping started on the second beat.) In part, this discrepancy is due to a "tuning in" at the beginning of the piece: the average initial asynchrony (on the second beat of Bar 1) was only slightly negative, and the typical average asynchrony was reached only after about three taps (cf. Fraisse, 1966; Semjen, Vorberg, & Schulze, 1998). It is not clear, however, what caused the deviation in the opposite direction in Bar 5. Another major discrepancy of unexplained origin can be seen in Bar 10 versus Bar 14. Nevertheless, the overlaid data are significantly correlated, which attests to the reliability of the systematic variation in the asynchronies. To compute the correlations between the asynchrony profile and the performance timing profiles, the initial three asynchronies were omitted and the whole asynchrony profile was shifted to the left by one position, for it was the asynchrony at the *end* of an IOI that was thought to reflect temporal expectations. Alas, the correlations with the performance timing profiles were disappointingly small. Only the one with the synchronised timing profile approached significance, which is at least consistent with the prediction that the asynchrony profile would be most closely related to the synchronised timing profile. However, the asynchrony profile does show a stronger, negative correlation with the detection accuracy profile, as predicted.

The tap timing profile is shown in Figure 2f. It represents the first difference of the asynchrony profile plus the duration of the constant baseline IOI (480 ms). Its correlations with the other profiles are modest but in the predicted direction and largely significant. Given that the relative intensities of the primary tones may have affected the perceived durations of the IOIs, it may be asked whether they also influenced the timing of the synchronised finger taps. There are two possibilities: anticipation of differences in subjective IOI duration, in which case there should be a direct (lag 0) correlation with tap timing; and tracking, in which case there should be a delayed (lag 1) correlation. The direct correlation between piano keypress velocity differences and tap IOIs was indeed significant and positive ($r = .34$, $df = 149$, $p < .001$), whereas the delayed correlation was not ($r = -.14$). This could be interpreted as a tendency to anticipate subjective changes in IOI duration caused by intensity differences among successive primary tones. However, the correlation was not higher within melodic eighth-note runs than elsewhere, which contrasts with the perceptual results.

EXPERIMENT 2

Experiment 2 constituted a replication of Experiment 1 with different music and one additional condition, a detection task with IOI decrements. In that respect it followed Repp (1998e), who had found a stronger correlation between the increment detection accuracy profile and the expressive timing profile (a negative correlation) than between the decrement detection accuracy profile and the expressive timing profile (a positive correlation). Owing to the different signs of the correlations, a "bias profile" representing the difference between the two detection accuracy profiles showed an even stronger correlation with the expressive timing profile. Accordingly, these were also the additional predictions for Experiment 2. The bias profile is believed to embody direction-specific temporal expectations in more pristine form than the increment and decrement detection accuracy profiles, which also reflect non-direction-specific variations in sensitivity that are largely removed when the difference between profiles is computed. The logic is similar to that underlying the beta index of signal detection theory (see, e.g., Macmillan & Creelman, 1991), though the method is more crude.

Repp (1998e) also computed a "sensitivity profile" by taking the average of the increment and decrement detection accuracy profiles, which is somewhat analogous to the d′ index of signal detection theory. The sensitivity profile was unrelated to the expressive timing profile, as it should be, since it is not direction-specific. Therefore, a sensitivity profile will not be discussed here. In contrast to typical psychophysical tasks, positional variations in bias are of greater interest here than positional variations in sensitivity because the bias is perceptual in origin, not a simple response bias.

Methods

The Music

The music was the complete Prelude No. 6 in B minor from Chopin's op. 28. The score is shown in Figure 3. The piece comprises 26 bars. The principal melody is in the left hand here, except for one brief episode (Bars 7–8) where a melody emerges in the soprano voice. Otherwise, the right hand has a steady accompaniment in pulsating eighth notes with harmonic support from quarter notes. The melodic passages contain a variety of note values, including sixteenth notes. Thus, in this piece (in contrast to Experiment 1) one cannot ignore the fact that there are IOIs of two metrical lengths, corresponding to sixteenth and eighth notes in the score. (There is one longer IOI in Bar 25, spanning three eighth notes.)

Performances

The pianists and procedure were the same as in Experiment 1. The recordings were made in the same session and in the same order. In the synchronised playing condition, the metronome was set at the rate of the eighth notes. Inter-onset intervals were measured from/to the onsets of left-hand melody notes where present (except in Bars 7–8, where the right-hand melody notes were considered primary) and from/to the top notes in the right hand elsewhere.

Figure 3
Prelude No. 6 in B minor, from op. 28 by Frédéric Chopin (Paderewski Edition, 1949).

Detection Task

Stimuli. Since the performances for this study had not yet been recorded when the detection task was set up, an expressive performance by the author, MIDI-recorded on the Roland RD-250s digital piano several years ago, served as the starting point. Although not of the same artistic quality as the performance from which the stimuli in Experiment 1 were derived, it seemed adequate for the purpose. To give the reader an idea of expressive timing in this piece, the performance is included as Sound Example 4.[9] An evenly timed version was created by the same method as in Experiment 1, with a baseline sixteenth-note IOI of 350 ms (Sound Example 5). Changes in IOI durations were made by the same method. There are 183 IOIs in the piece: 64 corresponding to sixteenth notes, 118 to eighth notes, and one (Bar 25) to three eighth notes. In contrast to Experiment 1, the sixteenth-note IOIs were modified individually, not as subdivisions of eighth-note IOIs. The changes introduced were 18%, 16%, 14%, 12%, and 10%, both increments and decrements. One blocks of eight trials was generated for each of these 10 conditions. In the course of these eight trials, each of the 183 IOIs was modified once. Thus, each trial contained about 23 modified IOIs, separated by at least four unmodified ones. A trial containing 14% decrements is presented as Sound Example 6.

Participants. Twelve summer students who had responded to an advertisement were paid for their participation. They had various degrees of musical training. The data of several additional participants were excluded because of high false alarm rates and/or poor detection scores, which were in some cases due to slow responding.

Procedure. The procedure was the same as in Experiment 1. Participants came for two sessions, some of them starting with the increment condition and others with the decrement condition. Each participant listened to three blocks of trials, with the level of difficulty of the second and third blocks chosen by the experimenter on the basis of the number of responses on the previous block. The initial block had 18% changes for participants early in the experiment, but when it became evident that performance was somewhat too high overall, later participants started with 16% or 14%. (The goal was again an average score of about 50% correct.) The three blocks in the second session were assigned the same proportional changes (but in the opposite direction) as the ones in the first session for that participant.

Synchronisation Task

Participants. Twelve paid volunteers participated, most of whom had also done the detection task. In addition, the author participated. One further participant's data were excluded because of exceptionally high variability.

Stimuli and procedure. After one practice trial, the evenly timed version of the music was presented 20 times, in four blocks of 5. Participants tapped along with the eighth notes, starting on the second beat of Bar 1, by pressing a white key on a Fatar Studio 24 MIDI controller (a silent three-octave keyboard) which they were holding on their lap. With this new device, there were hardly any missing taps in the recorded data, and keypress velocities were recorded along with key depression and release times.

Results and Discussion

The timing data are shown in Figure 4 in terms of eight profiles (Panels a–h). Each profile starts on a left-hand page (Bars 1–12) and continues on the facing right-hand page (Bars 13–26). The data for Bars 9–12 and 18–21 are overlaid on those of the rhythmically similar Bars 1–4 and 14–17, respectively. The melody notes are shown in musical notation on top of each page for guidance. In the performance timing and detection accuracy profiles, the results are shown separately for eighth- and sixteenth-note IOIs. The performance timing profiles for eighth-note IOIs (Figures 4a, 4b, 4c) continue through sixteenth-note passages because eighth-note IOIs could be calculated by adding successive sixteenth-note IOIs. However, the detection accuracy profiles for eighth-note IOIs (Figures 4d, 4e, 4f) are discontinuous because the average of the detection scores for changes in each of two adjacent sixteenth-note IOIs is not equivalent to the detection score for a change in the eighth-note IOI comprising the two sixteenth-note IOIs (a change that did not occur in this experiment). For graphic reasons, it was convenient to plot each eighth-note IOI as a pair of equal sixteenth-note IOIs; the long IOI in Bar 25 appears as a plateau of six data points. This graphic subdivision of eighth-note IOIs was not carried out in the tapping profiles (Figures 4g, 4h) because sixteenth notes did not play any role in the synchronisation task. The correlational statistics are summarised in Table 2.

The expressive eighth-note timing profile (Figure 4a) was less strongly modulated than that of Prelude No. 15 (Figure 2a), due in part to the considerably slower tempo. (The average eighth-note IOI was about 800 ms in Prelude No. 6 versus about 500 ms in Prelude No. 15.) Nevertheless, several pronounced ritards can be seen (in Bars 8, 14, 17, 21, 22, 23, 24, and 25). In addition, the timing of sixteenth notes showed characteristic patterns: in each group of four sixteenth notes, the initial and final IOIs were substantially longer than the two middle IOIs, which is very similar to the timing of melodic eighth-note runs in Experiment 1. When a single melodic

Table 2
Correlations Among the Profiles Shown in Figure 4, Separately for Eighth Notes (df = 142 to 149) and Sixteenth Notes (df = 62)

Profile	Level	ET	MT	ST	ID	DD	BP	AS	TT
Expressive timing (ET)	8th	.79***							
	16th	.97***							
Metronomic timing (MT)	8th	.74***	.76***						
	16th	.81***	.94***						
Synchronised timing (ST)	8th	.32**	.55***	.62***					
	16th	.77***	.96***	.90***					
Increment detection (ID)	8th	−.65***	−.45***	−.17	.65***				
	16th	−.57***	−.66***	−.69***	.75**				
Decrement detection (DD)	8th	−.25*	.14	.23*	.35**	.48**			
	16th	.42**	.64***	.64***	−.38*	.59*			
Bias profile (BP)	8th	.40***	.53***	.35**	−.64***	.49***	.51**		
	16th	.61***	.77***	.79***	−.93***	.69***	.81***		
Asynchronies (AS)[a,b]	8th	.39**	.50***	.26*	−.40***	.15	.48***	.56***	
Tap timing (TT)[b]	8th	.15	.19	.35**	−.21	.07	.25*	.29**	.38*

Note. The entries in the main diagonal represent the correlations between the overlaid portions of each profile (df = 46 for eighth notes, df = 20 for sixteenth notes).
[a] Shifted by one position to the left. [b] Initial data point absent and the next three data points omitted.
* $p < .01$. ** $p < .001$. *** $p < .0001$.

sixteenth note followed a dotted eighth note, so that its onset bisected the eighth-note IOI between the preceding accompaniment note and the following melody note (Bars 1, 3, 9, 11, and 23), the IOI following the sixteenth-note onset was always much longer than the one preceding it. In other words, the 3:1 ratio between the dotted eighth note and the sixteenth note was reduced (cf. Gabrielsson et al., 1983). These sixteenth-note timing patterns were remarkably consistent.

The metronomic timing profile is shown in Figure 4b. It is likely that the pianists' attention was focused on the eighth-note metrical level here, especially since the metronome ticks in the preceding synchronised playing condition were at the rate of the eighth notes. Nevertheless, systematic and reliable deviations from regularity occurred in the metronomic eighth-note profile. Much more striking and highly consistent deviations, however, can be seen in the timing of the sixteenth notes, either because the pianists did not include them in their conscious effort to play as regularly as possible, or because their timing seemed subjectively regular as it was (cf. Drake & Palmer, 1993). Moreover, the patterns of the deviations are highly similar to those in expressive performance for both eighth and sixteenth notes, as predicted.

The synchronised timing profile (Figure 4c) is quite similar to the metronomic timing profile, remarkably so at the sixteenth-note level. The extremely high correlation for sixteenth notes confirms that the pianists were not affected by the metronome at this lower metrical level, be it deliberately or involuntarily. At the level of eighth notes, the expressive timing profile is considerably more similar to the metronomic timing profile than to the synchronised timing profile, just as in Experiment 1.

The detection accuracy profiles are shown in Figures 4d, 4e, and 4f. There are three such profiles in this experiment: one for IOI increments (Figure 4d), another for IOI decrements (Figure 4e), and the difference between the two, the bias profile (Figure 4f). Following Repp (1998e), the bias profile was calculated by subtracting the increment profile from the decrement profile and dividing by two, so that it represents variations in the extent to which decrement detection was easier than increment detection. Note that the proportional changes in IOI duration were the same for increments and decrements.

It is evident that detection scores were much lower for sixteenth-note IOIs than for eighth-note IOIs, particularly in the decrement condition. Since the proportional changes were the same for eighth- and sixteenth-note IOIs, this difference suggests that Weber's law did not hold in the context of this music. The difference may well be attentional in origin, however: perhaps the listeners focused their attention on the higher metrical level, just like the pianists in metronomic and synchronised performance.[10] One consequence of the low sixteenth-note scores was that the eighth-note scores turned out to be rather high, because the experimenter adjusted the difficulty of the tasks on the basis of the total number of responses given (and moreover the detection task turned out to be somewhat easier overall than expected). However, there seemed to be no serious distortion due to ceiling effects in the profiles.

The internal consistency of the detection accuracy scores was satisfactory. The correlations of the overlaid data are higher if eighth-note and sixteenth-note scores are combined: .75 for increments, .88 for decrements, and .71 for bias (all df = 68, p < .0001). Surprisingly, there was a positive correlation between the detection accuracy profiles for increments and decrements, though only at the eighth-note level and overall; it was .42 (df = 183, p < .0001) for eighth- and sixteenth-notes combined. This means that contextual factors affecting listeners' sensitivity to local timing deviations (regardless of direction) outweighed direction-specific temporal expectations. Nevertheless, the bias profile provides a rough measure of these temporal expectations, to the extent that they were present.

The correlations between the detection accuracy and performance timing profiles are largely in agreement with the predictions. The increment detection accuracy profile showed significant negative correlations with the timing profiles at both the eighth-note and sixteenth-note levels. However, while the sixteenth-note increment detection scores correlated substantially with all three timing profiles, the eighth-note increment detection scores correlated more strongly with expressive than with metronomic timing, and not even significantly with synchronised timing. This refutes again (as in Experiment 1) the prediction that detection accuracy would be

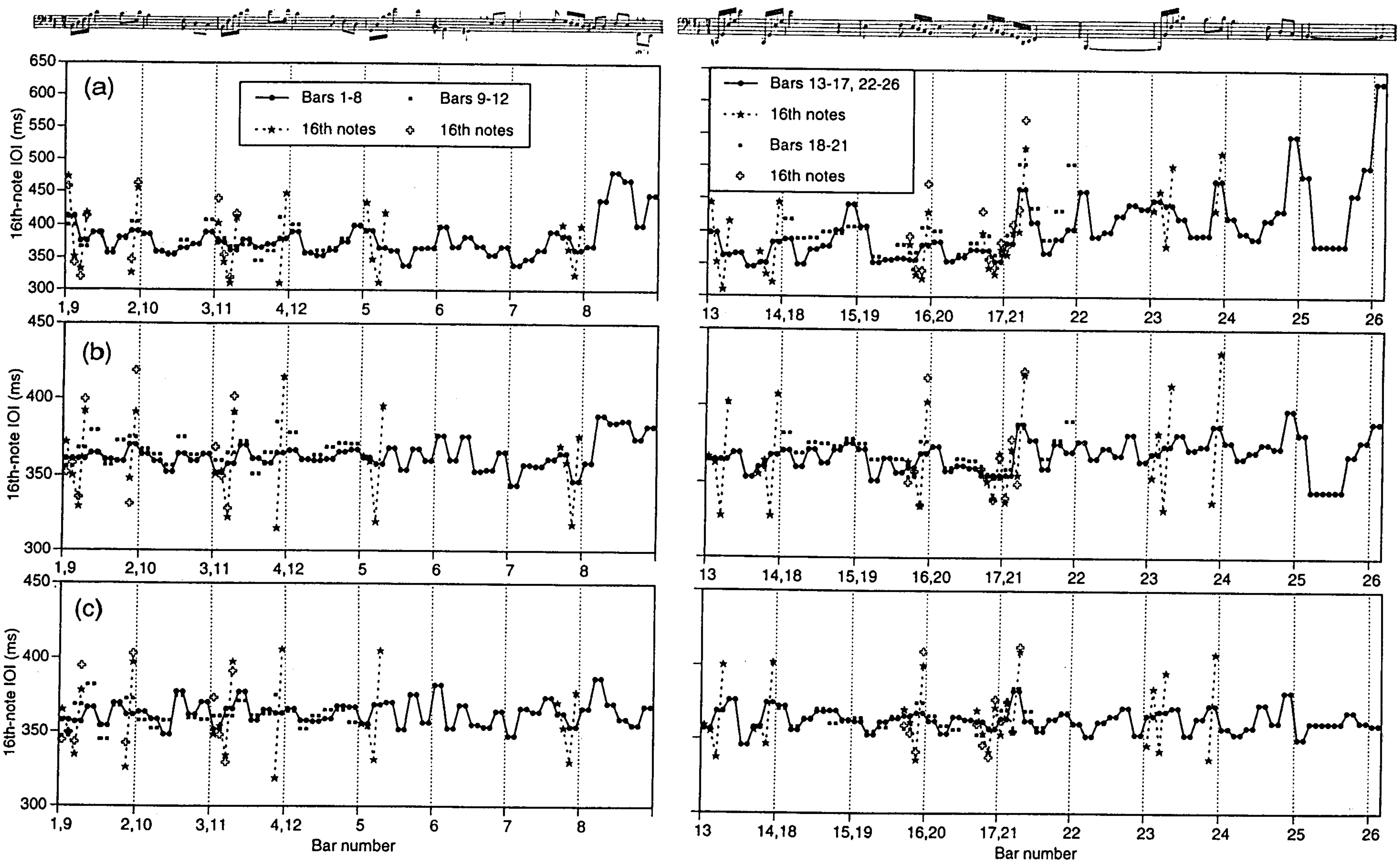

Figure 4 (a, b, c)
Data profiles of Experiment 2: (a) expressive timing profile, (b) metronomic timing profile, (c) synchronised timing profile.

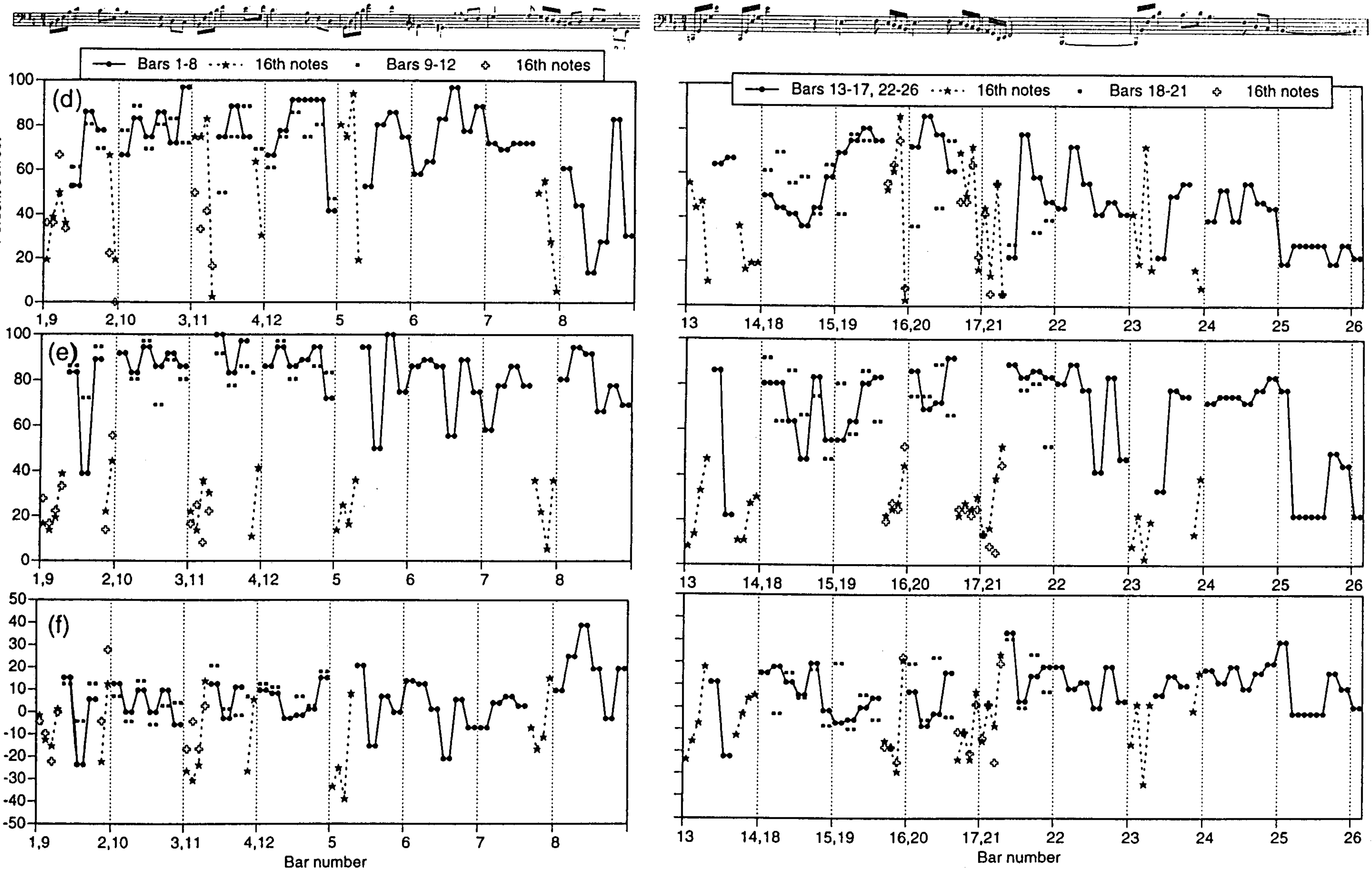

Figure 4 (d, e, f)
Data profiles of Experiment 2: (d) increment detection profile, (e) decrement detection profile, (f) bias profile.

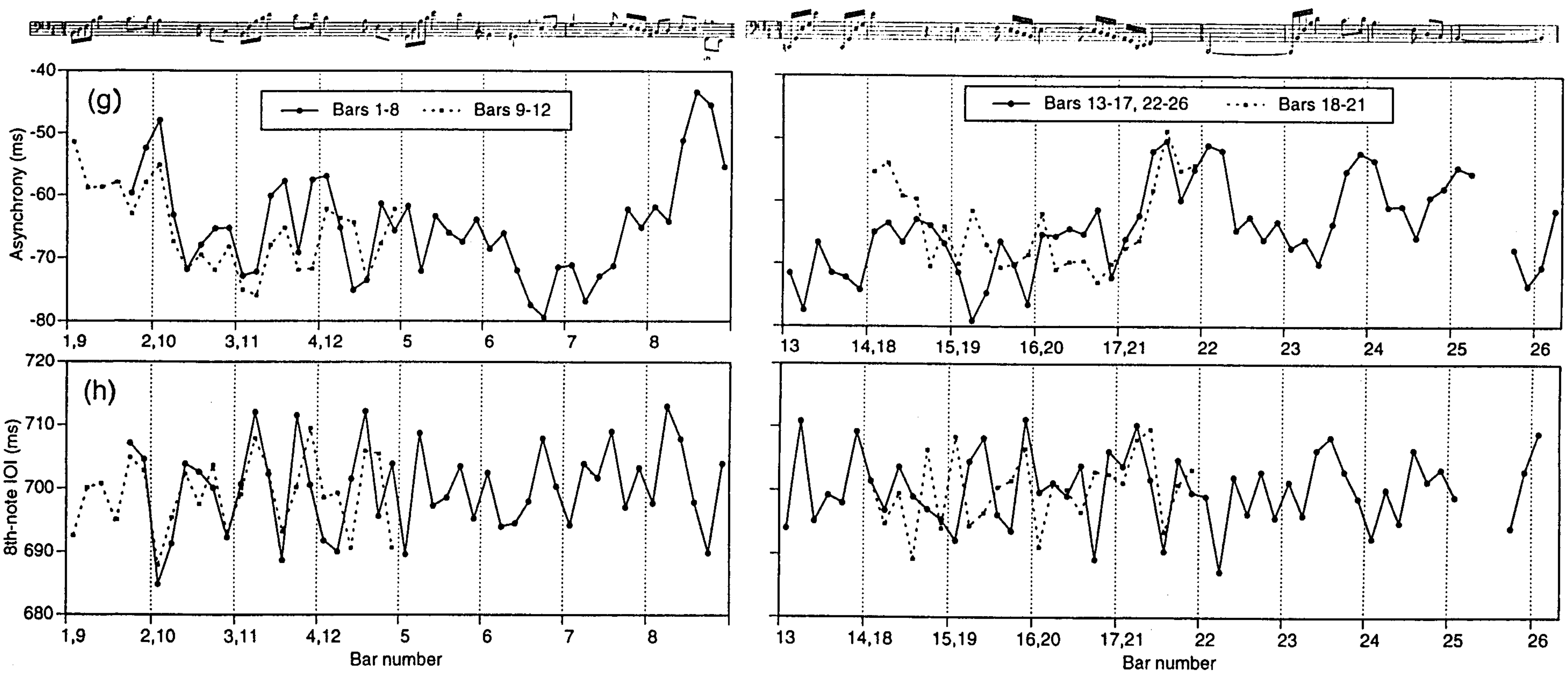

Figure 4 (g, h)
Data profiles of Experiment 2: (g) asynchrony profile, (h) tap timing profile.

more closely related to involuntary timing variation than to deliberate expressive variation.

The decrement detection accuracy profile was expected to be positively correlated with the timing profiles. This was true at the level of sixteenth notes. However, for eighth notes there was a weak positive relationship with synchronised timing only and a weak negative relationship with expressive timing (which is obviously connected with the positive correlation between the increment and decrement detection accuracy profiles for eighth notes). These results confirm Repp's (1998e) observation that the decrement detection accuracy profile is less clearly related to expressive timing than is the increment detection accuracy profile. Repp attributed this to temporal expectations being mainly in the form of lengthenings (which mark boundaries and accents and thus have expressive significance) rather than shortenings (which tend to be less important in expressive timing).

Finally, again as predicted, the bias profile was more strongly correlated (in absolute terms) with the performance timing profiles than was either the increment or the decrement profile, except in the case of expressive timing at the eighth-note level, where the increment and decrement correlations had the same sign and therefore could not be improved upon by computing difference scores. In fact, the bias profile was more highly correlated with the metronomic than with the expressive timing profile at both metric levels, which is consistent with a prediction that was not upheld by the increment detection accuracy profile alone, namely that detection accuracy would be more closely related to involuntary than to voluntary timing.

As in Experiment 1, the detection accuracy scores were significantly correlated with the relative intensities of the tones delimiting IOIs. Increment detection scores showed a small negative correlation with keypress velocity differences (first minus second tone) ($r = -.17$, $df = 181$, $p < .05$), decrement detection scores showed a larger positive correlation ($r = .34$, $p < .001$), and bias scores showed an even larger positive correlation ($r = .48$). Correlations of similar magnitude (.44 to .54) were shown by bias scores for melody-melody, accompaniment-melody, and accompaniment-accompaniment IOIs separately, but not by melody-accompaniment IOIs ($r = -.01$). Melody-melody IOIs could be subdivided into eighth-note and sixteenth-note IOIs; the latter showed a larger correlation than the former ($r = .50$, $df = 61$, $p < .001$, vs. $r = .25$, $df = 30$, *ns*). In sum, IOI increments were generally harder to detect and IOI decrements were easier to detect the louder the first tone was relative to the second tone.

The asynchrony and tap timing profiles are shown in Figures 4g and 4h. The asynchronies were more negative here than in Experiment 1, almost certainly due to the use of a different, silent response key (cf. Aschersleben & Prinz, 1997). The initial data point is missing because tapping started on the second half-beat. The following three data points showed the "tuning-in" phenomenon observed also in Experiment 1 (i.e., less negative or even positive values initially) and have been omitted from the graphs (to obtain better resolution along the *y* axis) and from the correlations in Table 2. The gap in Bar 25 is due to the fact that there were no note onsets during the long IOI, so that no asynchronies could be computed. Since the tap timing profile was derived from the asynchrony profile, it shows a similar gap in Bar 25.

The asynchrony profile (shifted to the left by one position in the computation of correlations) showed all the predicted significant correlations, even though they were only of moderate size: it correlated positively with the performance timing profiles (most highly with the metronomic timing profile) and with the bias profile, and negatively with the increment detection accuracy profile. Only the correlation with the decrement detection accuracy profile did not reach significance. The correlations for the tap timing profile showed a similar pattern but were much weaker, reaching significance in only two instances. This contrasts with the results of Experiment 1, where tap timing showed a stronger relation to performance timing and detection accuracy than did the asynchronies. To determine whether the tap timing profiles may have been influenced by the relative intensities of the musical tones, the lag 0 and lag 1 correlations with the primary-tone keypress velocity differences were calculated, for eighth-note IOIs only. As in Experiment 1, the lag 0 correlation reached significance ($r = .21$, $df = 113$, $p < .05$), whereas the lag 1 correlation did not. However, the correlation is too small to have much explanatory value.

Research on simple isochronous finger tapping has shown that, at moderate tempi, tap IOIs tend to be shorter immediately before a deliberately accented tap and longer immediately afterwards (Billon & Semjen, 1995; Billon, Semjen, & Stelmach, 1996; Piek, Glencross, Barret, & Love, 1993; Semjen & Garcia-Colera, 1986). This finding corresponds to the perceptual timing distortions caused by accented events (Woodrow, 1909; Tekman, 1995, 1997): intervals that are typically shortened in production tend to be perceived as relatively long in an isochronous stimulus sequence, and vice versa. When no accents are intended, a similar but very weak relationship between tap force and surrounding tap IOIs has been observed (Keele, Ivry, & Pokorny, 1987). It is conceivable that the systematic variations in tap timing were caused in part by systematic variations in tap force in response to the music (cf. Repp, 1999b). This issue could not be addressed in Experiment 1, but in Experiment 2 keypress velocities and key dwell times — two rough measures of finger kinematics — were recorded and could be examined in relation to tap timing. Average keypress velocity varied only minimally in the course of the music and was uncorrelated with the asynchrony profile ($r = -.02$) and the tap timing profile ($r = -.12$). Average key dwell time varied slightly around a mean of about 200 ms and was likewise uncorrelated with asynchronies ($r = -.11$) but exhibited a small positive correlation with tap timing ($r = .24$, $df = 146$, $p < .01$), which is not surprising: longer dwell times went with longer IOIs between taps. The hypothesis that variations in tap timing were caused by variations in tap force can be rejected.

GENERAL DISCUSSION

The present study replicates and extends some earlier findings, but it also tempers some earlier conclusions.

One earlier observation (Palmer, 1989; Penel & Drake, 1998; Repp, 1999a) that was fully replicated was that metronomic timing is patterned similarly to expressive timing, even though it is much less modulated. In both experiments, this correlation was nearly as high as the reliability of the metronomic timing profile itself (i.e., the correlation of its overlaid portions). Although it is possible that the systematic timing variation in metronomic playing merely reflects an insufficient effort by the pianists to suppress their expressive urges, it seems likely that it is at least in part an unavoidable consequence of the processing of musical structure. Structural processing, and perceptual/cognitive grouping in particular, seems to interact with the perception and production of timing (Penel & Drake, 1998; Repp, 1998a).

The synchronised playing condition was novel. As one should expect if structurally induced timing effects are unavoidable, the synchronised timing profile was highly similar to the metronomic timing profile. Again, the correlation was about as high as the reliability of the former, though somewhat lower than the reliability of the latter, especially in Experiment 2 (at the eighth-note level). This correlation might suggest that the pianists simply did the same thing in the two conditions. However, expressive timing correlated more highly with metronomic than with synchronised timing in both experiments. This must be due to the additional constraint imposed by the external metronome, namely the requirement to stay in synchrony, which necessitates error correction (see, e.g., Mates, 1994; Pressing, 1998; Vorberg & Wing, 1996). Error correction introduces a negative correlation between adjacent IOIs and thus tends to smooth the pattern of systematic timing variation. This was confirmed by computing the first-order ("lag 1") autocorrelations of the timing profiles. These autocorrelations were positive for expressive timing ($r = .45$ in Experiment 1, $r = .62$ for eighth notes in Experiment 2), which reflects the coherent variation of this form of timing (cf. Repp, 1999a). The autocorrelations for metronomic timing were likewise positive, but clearly smaller ($r = .18$ in Experiment 1, $r = .34$ for eighth notes in Experiment 2). The autocorrelations for synchronised timing, however, were negative, as predicted ($r = -.28$ in Experiment 1, $r = -.17$ for eighth notes in Experiment 2). Since error correction coexists with residual coherent timing variation, which causes a positive autocorrelation (as in metronomic timing), the negative autocorrelation due to error correction alone must have been stronger than these values indicate.

The sixteenth notes in Experiment 2, which represent a metrical level below the internal or external metronome beat, did not seem to participate in metronomic and synchronised timing. Although their relative timing was affected somewhat by the regularisation at the eighth-note level, it remained highly similar to the sixteenth-note timing in expressive performance, and this was equally true in metronomic and in synchronised playing. These results demonstrate that it is possible to regulate timing at a higher metrical level without much effect on timing at a lower metrical level. It is likely that the timing variations at the sixteenth-note level represent obligatory effects of rhythmic grouping that are perceived as subjectively regular (Drake & Palmer, 1993; Penel & Drake, 1998). The result is also consistent with Clarke's (1987) view that metrical timing is governed by an internal or external timekeeper, whereas timing at submetrical levels in music performance is achieved "by means of procedures which specify abstract movement patterns that take on a particular temporal profile in the course of their execution" (p. 222).

Although the negative correlations between the detection accuracy profiles for IOI increments and the expressive timing profiles in the two experiments replicate earlier findings (Repp, 1992c, 1998e, 1999b), they are conspicuously weaker, especially the one in Experiment 1. The correlation of $-.86$ for a short excerpt from a Chopin Etude (Repp, 1999b: Exp. 1) contrasts with correlations of $-.40$ in Experiment 1 and $-.65$ in Experiment 2 (eighth notes). These differences indicate that the relationship between expressive timing and the detectability of hesitations in a strictly metronomic performance is not as tight as the results of Repp (1998e, 1999b) suggested. One possible cause of the weaker correlations could be the sheer length of the present musical materials. Perhaps the participants' attention waned during the later portions of the music and caused erratic detection performance. In that case, correlations should have been stronger initially in each piece. This was checked by computing the correlation between increment detection and expressive timing over the initial eight bars only, which roughly corresponds to the length of the excerpts used in previous studies. Indeed, these correlations were more pronounced: $-.55$ in Experiment 1 and $-.77$ in Experiment 2 (eighth notes). However, this cannot be the whole story. There was evidence for systematic patterns in the detectability scores that were unrelated to expressive timing and occurred after Bar 8. It appears that the intensity relationships of successive primary notes exerted an effect on subjective time perception (cf. Woodrow, 1909; Tekman, 1995, 1997) that was somewhat independent of the temporal expectancies induced by melodic-rhythmic grouping. In earlier materials, there may have been greater congruence between expressive dynamics and grouping structure than in the present pieces, and this may have led to the stronger correlations.

One might ask why dynamic variation was not removed from the music to begin with. Although this may be a useful exercise in a future study, the goal here was to tamper with the music as little as possible. Expressive variation is an integral part of music whose removal results in an impoverished and unrealistic stimulus. While the removal of timing variation was necessary for the detection experiment, that of dynamic variation was not. Of course, greater realism implies greater complexity.

In both experiments, increment detection accuracy (at the eighth-note level) correlated less strongly with metronomic timing than with expressive timing. This result is contrary to expectations and suggests that some of the factors that obligatorily constrain detection performance have non-obligatory effects on timing that can be suppressed in metronomic performance. Penel and Drake (1998) have argued plausibly that it is the higher levels in the hierarchical phrase structure whose effects on timing are under voluntary control, whereas effects of low-level grouping on timing are unavoidable. This leads to the inference that increment detection may be influenced by higher as well as lower levels in the grouping structure, as already noted by Repp (1992c). However, in contrast to the results at the eighth-note level, increment detection at the sixteenth-note level in Experiment 2 correlated more highly with metronomic (and synchronised) than with expressive timing. Since sixteenth-note timing presumably reflects only effects of low-level grouping, this result is consistent with the hypothesis that local obligatory effects are shared by the different tasks.

Experiment 2 confirmed earlier findings that decrement detection is not the mirror image of increment detection. Repp (1998a, 1998e) found a significant negative correlation between these two detection accuracy profiles in only one of eight related experiments. Here there was a negative correlation at the sixteenth-note level, but a positive correlation at the eighth-note level. As suggested earlier, the positive correlation may have been due to structurally induced variations in nondirectional sensitivity to timing perturbations that exceeded the temporal expectations that were of real interest in this study. These temporal expectations were probably better reflected in the bias profile than in either detection accuracy profile. The bias profile, as it turned out, did correlate more highly with the metronomic timing profile than with the expressive timing profile at both the eighth-note and sixteenth-note levels. Perhaps, then, the hypothesis that links detection accuracy to metronomic timing via shared determinants of obligatory variation is supported, after all.

The results of the synchronised tapping task were only weakly related to the timing and detection accuracy profiles. Nevertheless, the significant correlations were in the predicted direction and tend to replicate Repp's (1999b) findings. The correlation between tap timing and synchronised timing was significant in both experiments and was stronger than the mostly nonsignificant correlations of tap timing with expressive and metronomic timing. This makes sense in terms of the shared constraint imposed by synchronisation. Whereas asynchronies showed no relation to performance timing in Experiment 1, they correlated positively with all three timing profiles and especially with metronomic timing in Experiment 2. The reason for this difference between experiments is not clear. Asynchronies also correlated negatively with increment detection in both experiments, more so than did tap timing. The negative correlation means that taps tended to occur later at the ends of IOIs in which increments were difficult to detect, that is in which lengthening was expected. This apparent influence of musical structure on motor control warrants further detailed investigation.

On the whole, the present results lend support to the general hypothesis that timing production, timing perception, and perceptual-motor coordination are all interrelated within the same musical context, though perhaps not as tightly as was previously believed. The principal factor responsible for the between-task correlations is the hierarchical grouping structure of the music, but different tasks may be differentially sensitive to different levels of grouping as well as to other properties of the music. To tease apart the multiple factors that may be involved, more analytic experiments, such as begun by Repp (1998e), will be necessary.

Footnotes

1. Effects of perception and memory are generally confounded in these experiments because the music is always familiar to the participants, be they performers (who must rehearse it to play it fluently) or listeners (who must listen to many repetitions of it in order to yield sufficient data for a detection accuracy profile).

2. In the given hardware configuration, MAX plays back about 2.4% faster than specified in MIDI instructions and records MIDI timings correspondingly slower. This constant scaling factor was disregarded in all data analyses, which are based on the input and output of MAX.

3. A MIDI instruction consists of a time, an event parameter, a pitch code, and a keypress velocity.

4. The notation shows the melody of Bars 5–8 (rather than 1–4), 9–12, and 17–19, separated by double bars. The septuplet ornament in Bar 4 would have been difficult to render adequately in this small notation, and is irrelevant to the profiles.

5. This is the average timing profile of the eight pianists' performances, not of the individual performance from which the stimuli for the detection and synchronisation tasks were derived (Sound Example 1). The specific timing pattern of the latter is not believed to have any particular relevance. Once removed, it could not be recovered from information remaining in the music, such as expressive dynamics. At the level of detail that is of interest here, there seems to be little relation between expressive timing and dynamics (Repp, 1996b, 1999c). Moreover, the timing profile of Sound Example 1 is more individual and less representative of typical expressive timing than the average profile shown in Figure 2a; their correlation is only .68 ($df = 148$, $p < .0001$). For a justification of averaged timing data, see Repp (1997, 1998b).

6. A few systematic differences can be readily explained: the initial IOI of the piece (Bar 1) is elongated relative to the corresponding IOI in Bar 5, which is a common start-up phenomenon; the two longish IOIs preceding the very long (omitted) IOI at the end of Bar 4 are connected with the septuplet ornament that does not occur in Bar 8; the difference between Bars 9 and 13, towards their end, is connected with a wide left-hand chord that appears in Bar 9 but not in Bar 13; and the difference in the transition from Bar 10 to Bar 11 versus that from Bar 14 to 15 is related to the key modulation, suspended downbeat, and wide left-hand spans that all occur in the latter bars, but not in the former.

7. The profile shown here is very similar ($r = .93$, $df = 148$) to the average timing profile of a set of expressive performances recorded several years earlier, from which the performance was drawn on which the stimuli for the detection and synchronisation tasks were based. In that earlier study, ten graduate students of piano at the Yale School of Music each had played the complete prelude three times on a Yamaha Disklavier (see, e.g., Repp, 1996a). In an earlier conference presentation (Repp, 1998d), the detection and synchronisation results of Experiment 1 were compared to the average expressive timing profile of this earlier set of performances, with results similar to the ones reported here.

8. The correlation becomes impressive if the immediately following melody-accompaniment IOI is included with each eighth-note run ($r = -.81$, $df = 29$, $p < .0001$).

9. The timing pattern of this performance is quite typical. Its correlation with the average timing profile of the eight pianists recorded for this study (Figure 4a) is .86 at the eighth-note level and .85 at the sixteenth-note level.

10. Since a change in a sixteenth-note IOI caused a change half as large in the superordinate eighth-note IOI, it could be argued that the low scores for sixteenth-note IOIs reflect the detectability of the change in the eighth-note IOI. In that case, however, there should be no difference between the detection scores for the component sixteenth-note IOIs, and this is clearly not true. Therefore, the detection scores for sixteenth-note IOIs do reflect the detectability of changes in these short IOIs, though they were perhaps less attended to.

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